ULTRASONIC WELDING PROCESS AND EQUIPMENT FOR CONSTRUCTION OF ELECTRON-TUBE MOUNTS

Third Quarterly Progress Report
For the Period
January 1 through March 31, 1963

Contract No. DA-36-039-sc86741
Order No. 19063-PP-62-8181

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AEROPROJECTS INCORPORATED
West Chester, Pennsylvania

ULTRASONIC WELDING PROCESS AND EQUIPMENT FOR CONSTRUCTION OF ELECTRON-TUBE MOUNTS

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The object of this program is to design and construct prototype welding equipments and their associated accessories to perform by ultrasonic techniques the welding operations required in the assembly of electron tubes under Specifications SCS-114A and SCIPPR-15.

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ABSTRACT

Results of welding all the required combinations of materials and geometries are presented. Tensile-shear strength data and metallographic evaluation for successfully welded combinations are reported. The requirements for ultrasonic welding in the manufacture of three specific electron tubes have been established.

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PURPOSES

The objectives of this Production Engineering Measure (PEM) are to:

1. Demonstrate the capability limits of ultrasonic welding to join combinations of metallic materials of interest to the electron-tube industry. This part of the work will be limited in that it will not continue exhaustive attempts to weld those combinations which might prove particularly difficult to join.

2. Analyze the welding requirements for three specific electron tubes. The three tube types selected are the Type 6080WB, 5814WB and 6205. These were selected by the U. S. Army Electronics Materiel Agency because they are widely used in military equipment, and have a record of failures due to improperly welded joints.

3. Prepare fixturing and tooling for the specific electron tubes, so that ultrasonic welding may be used in the manufacturing process.

4. Weld the parts required to assemble electron-tube mounts for the three tube types, and evaluate.

5. Build production ultrasonic welding equipment which will enable an electron-tube manufacturer to make the welded connections in a broad range of electron-tube types.

6. Install the ultrasonic welding equipment in a production company, and produce on a pilot basis with that company's personnel, a limited lot size of each of the three tubes for subsequent evaluation in accordance with applicable military specifications.

I. NARRATIVE AND DATA

A. Welding Study

Studies were completed to demonstrate the capability of joining 51 metal combinations in wire to flat sheet material by ultrasonic welding. The investigation involved a total of 91 weld specimens in two wire sizes, for a total of 182 combinations. Junctions were successfully effected in virtually all of the desired similar and dissimilar metal combinations, demonstrating that ultrasonic welding produces satisfactory welds in a wide range of material combinations of importance to the electron-tube industry. These welds were evaluated by means of tensile-shear tests and metallurgical examination, as outlined in Section I, Basic Data, Second Quarterly Progress Report. Shock and vibration tests are not yet complete.

The welding study of the various material combinations was limited by the scope of the Production Engineering Measure (Objective 1 under Purposes). Normally, when optimum weld quality is sought, metallurgical and strength data are thoroughly analyzed, and the results of the observations are applied to a continuing series of weldment specimens. Each individual material-geometry combination could be the subject of an extended investigation during which such factors as welding machine settings, surface preparation, the use and composition of interleaves, etc, would be considered as to their effect on the quality of ultrasonic welds.

This program did not involve an investigation of such scope. However, more extensive study was given to those materials of particular interest to the electron-tube industry, e.g., molybdenum, tungsten, nickel, etc.

To simplify identification of the various materials, each wire-to-coupon specimen group was assigned a number, used throughout this report. The numbers are listed in Tables I and II.

1. Material Procurement

Within the limitations of this program, the small quantities and large number of metals involved made it impossible to set up specifications for receiving inspection that would insure the desired quality of metals and alloys.

To establish consistent bench marks in the properties of the materials, available literature and technical data were studied. Much of the information, particularly that relating to refractory metals, was contradictory. In addition, liaison was established with the Cleveland, Ohio, plant of the General Electric Company, producers of molybdenum and tungsten sheet and wire, who supplied very helpful information as well as high-quality materials providing different surface conditions, but the program had advanced to a point where this material could not be utilized.

2. Tooling

The tooling used in making the ultrasonic welds is described in the Second Quarterly Progress Report.

Under some circumstances during preliminary efforts to ultrasonically weld some assemblies, vibratory resonance of one or more components of the assembly may be observed. Ordinarily this is of minor importance, requiring no difficult corrective measures to achieve satisfactory production procedures. This problem is characteristic of ultrasonic welding just as short circuiting through a previously made weld is characteristic of resistance welding. Occasionally parts resonance can be of sufficient violence to fracture a previously made weld or even some part of an assembly.

Corrective measures involve parts restraint (clamping) and ordinarily this is readily accomplished in the tooling and fixtures. If the assembly does not involve tooling and the welds are accomplished by simply inserting the parts between the sonotrode and anvil, it may be necessary to attach small masses such as washers by means of spring or screw clamps, or the parts themselves can be clamped together in similar fashion.

There is no known record of an assembly of parts that could not be ultrasonically welded reproducibly after parts resonance was properly suppressed.

3. Welding of Heavy Wires

a. Copper Coupon (Specimen Combination Nos. 1 through 11)

Welds with joint efficiencies from 87 to 100 percent were obtained with all wires of this first group except molybdenum, mild steel, stainless steel, and tungsten. These latter materials produced bonds of somewhat inadequate strength or consistency. Surface preparation before welding consisted of lightly abrading both the coupon and wire with 600-grit silicon carbide paper.

Work done later in the program indicated that improvement in the weldability of hard wire/soft coupon combinations could be effected by flattening the wire before welding. This technique provided a larger contact area and restricted intrusion of the wire into the softer material. Improvement in the weldability of molybdenum and tungsten was similarly effected by removing surface contamination by electropolishing. However, these methods of material preparation were not subsequently applied to this group because of limitations of scope in this phase of the program.

b. Gold Coupon (Specimen Combination Nos. 12 through 17)

Weld efficiencies from 95 to 100 percent were obtained with all wire materials in this group except stainless steel. Both the nickel and AISI 1010 steel wires were flattened prior to welding. Completely successful welds between gold and the AISI 304 stainless steel wire were not obtained by this method. Reannealing the wire after the cold deformation of the flattening operation should improve the weldability of this combination.

No surface cleaning was performed on either the gold coupon or wires of this group.

c. Molybdenum Coupon (Specimen Combination Nos. 18 through 25)

Electropolishing the molybdenum coupons resulted in successful welds with some wire combinations after initial attempts to weld the coupons in the "as received" condition failed.

Prior experience (1, 2) has shown that molybdenum and its alloys can be ultrasonically welded, but the material is prone to cracking under conditions which are not yet completely understood. Many researchers have reported cracking in molybdenum during fusion welding (3-19). Levy et al., (3, 4, 5) and Platte (7) use the term "catastropic" (i.e., unexpected, uncontrolled) cracking during attempts to fusion weld the material. Surface contamination by oxygen and nitrogen is believed to be responsible for the low ductility of molybdenum at room temperature (3-10). Removal of surface contamination and irregularities by grinding, etching, chemical milling, or electropolishing has been reported to improve ductility (3-8, 10, 11). Kuebrick (12) suggests that molybdenum contaminated by oxygen and nitrogen displays ductility in bend testing but may be brittle under other stress conditions because of carbide precipitation. Interstitial elements tend to diffuse toward grain boundaries because of low solubility (13) and promote cracking (7) of molybdenum.

Molybdenum coupons and wires were procured from Chatham Electronics Corporation as well as Fansteel Metallurgical Corporation. One group of the Chatham wires exhibited a dull appearance; the other, bright. The dull wires could not be welded, but the wires with the bright surface were successfully welded to stainless steel (No. 59) and titanium coupons (No. 79). Attempts to weld molybdenum wires to molybdenum coupons produced joint efficiencies of 55 percent.

The depth of surface contamination of the molybdenum wire and sheet was determined by metallographic methods after the material was recrystallized in dry argon for 10 minutes at 2450°F. Results of this study are presented in Figure 1.

Removal of the contaminated surface was initially attempted by chemical etching in an aqueous solution of nitric acid and hydrogen fluoride at 120°F, followed by immersion in Murakami's etch and final rinsing in water. This method was expected to remove uniformly 0.001 to 0.0015 inch per minute. Actual etching trials indicated removal of only 0.0025 inch after 11 minutes. Surface removal was not uniform, pits were formed, and the solution was quickly depleted.

Surface preparation was finally effected by electropolishing in a solution of 20 grams sodium hydroxide, 20 grams sodium nitrite, and 20 milliliters water. The solution required continuous stirring and the temperature was maintained at 50°C by water cooling. Approximately three to five minutes were required to remove about 0.001 inch from the diameter of the wires. Five to six minutes removed 0.001 to 0.002-inch from the surface of the coupons.

Ultrasonic welding of the electropolished wires and coupons produced a joint efficiency of 86 percent. Nickel and tantalum wires were joined to the electropolished molybdenum coupon with joint efficiencies of 100 percent. The stainless steel wire welds displayed less satisfactory strength properties. An average joint efficiency of only 40 percent was obtained. The combinations require more effort to permit making reproducible welds of high quality at this time. The work done to date indicates that further investigations of this material are required to delineate the factors controlling ultrasonic weldability. The physical and mechanical properties of molybdenum are listed in Table IV.

d. Nickel Coupon (Specimen Combination Nos. 26 through 36)

All the wires in this group were successfully welded to the nickel coupon. Joint efficiencies ranged from 76 to 100 percent using a spherical radius welding tip. Deformation of the softer wires can be reduced by using a grooved welding tip.

e. Rhenium Coupon (Specimen Combination Nos. 37 through 44)

Only half of the wires in this group were successfully welded. Joint efficiencies ranged from 74 to 100 percent. Rhenium wire and sheet received from the same vendor at different times varied in welding behavior. The wires, in particular, were occasionally subject to longitudinal and transverse cracking. Metallographic examination revealed porosity in the wire and Vickers microhardness measurements indicated minor differences from lot to lot.

Both rhenium wire and the adjacent area of the coupon are heated sufficiently during welding to produce oxide tints as described in Table III. The colors produced may be characteristic of the

type of oxide formed or are interference tints produced by light refraction. Enveloping the weld area with argon gas supplied by jets adjacent to the sonotrode eliminated oxidation, but did not improve weldability. Additional studies of rhenium and its welding behavior will unquestionably solve most of the problems encountered with these combinations. The physical and mechanical properties of rhenium are listed in Table IV.

f. Silver Coupons (Specimen Combination Nos. 45 through 50)

Successful welds were made with copper, gold, nickel, and silver wires. Joint efficiencies of 90 to 100 percent were obtained. Somewhat less successful welds were made between the mild steel wire (flattened) and silver sheet. Efficiencies of these test specimens averaged 61 percent.

g. Mild Steel (AISI 1010) Coupon (Specimen Combination Nos. 51 through 56)

All the required combinations were welded successfully except Combination No. 54 (silver wire). Joint efficiencies of 73 to 100 percent were obtained.

h. Stainless Steel Coupon (AISI 304) (Specimen Combination Nos. 57 through 67

Welds with gold, silver, and titanium wires (Nos. 58, 62, and 66) were not successful with either a spherically radiused or grooved tip. Only partial success was achieved with copper wires using a spherical radiused tip. Inconsistent results were obtained with the nickel wire using the spherical contoured tip. However, good results were achieved with a grooved sonotrode tip. Joint efficiencies of this group ranged from 83 to 100 percent for the successful combinations.

i. Tantalum Coupon (Specimen Combination Nos. 68 through 75)

All the combinations in this group except Nos. 68 and 69 (copper and molybdenum wires) were welded successfully with joint efficiencies between 72 and 100 percent. Degreasing in acetone was the only surface preparation used for the tantalum coupons.

j. Titanium Coupon (Specimen Combination Nos. 76 through 83)

All the welds, with the exception of the copper wire (No. 78), were satisfactory in this group with joint efficiencies from 72 to 100 percent. In addition, although satisfactory welds were obtained between the rhenium wire and titanium sheet, the reverse

combination (e.g., titanium wire to rhenium coupon) was unsuccessful. A more thorough study of the materials and influence of parts geometry on welding would contribute significantly to an explanation of this phenomena.

k. Tungsten Coupon (Specimen Combination Nos. 84 through 91)

Table IV presents the physical and mechanical properties of tungsten. Tungsten is difficult to join by all welding processes, including fusion and resistance welding. Embrittlement seems to be a basic problem. Literature research produced a better understanding of the characteristics of tungsten.

The interstitial content likely to be maintained in tungsten in solid solution after moderate cooling rates, as compared to those usually found in commercially available metals (13), is shown in Table V. Excess interstitials tend to be located on grain boundaries and produce a serious embrittlement effect. Embrittlement may be caused by metallic impurities (iron, chronium, calcium, nickel) (13) or by surface conditions (notches) (15, 16). A combination of mechanical notches and grain boundary conditions may reduce ductility (17).

To remove surface imperfections and contamination, tungsten wires were electropolished by a procedure similar to that used for molybdenum coupons. The diameter of the wire was reduced by about 0.005 inch. The coupons were first surface ground to a depth of about 0.003 inch, and subsequently electropolished to an additional depth of about 0.002 inch.

Tungsten wire welded to hard dissimilar metals attained a bright heat during ultrasonic welding. Distinct tints either on the coupon or on the wire, as described in Table VI, were observed.

Copper and tungsten (Combination Nos. 11 and 84) could not be welded because of the difference in hardness between the two. The tungsten wire cut through the copper coupon, and the copper wire was crushed onto the surface of the tungsten coupon.

Welds were successfully made between tungsten wires and AISI 304 stainless steel coupons (Combination No. 67) with the tungsten wires in the "as received" condition, and using a spherical-radius sonotrode tip. No welds could be made between annealed stainless-steel wires and tungsten coupons (Combination No. 88) in the "as received" condition. The welds did not improve by flattening the stainless-steel wires by 50 percent, and grinding and electropolishing the tungsten coupons. The stainless-steel wire (not flattened) was welded satisfactorily to the ground and electropolished tungsten coupon only by using a grooved sonotrode tip.

To make successful joints between the tantalum wire and tungsten coupon (Combination No. 89), it was necessary to use a grooved sonotrode tip and ground electropolished tungsten coupon.

Occasional welds of moderate strength could be made between titanium wire and tungsten coupon (Combination No. 90). Grinding and electropolishing tungsten coupons, the use of a grooved sonotrode tip, or flattening the titanium wire did not improve weldability. The use of a tantalum-foil interleaf did not improve welding.

Welds could not be made between tungsten wire and tungsten coupon (Combination No. 91) with materials in the "as received" condition. Welding occurred along a narrow line, but the wires split or cracked. The tungsten wires were then ground flat on one side to obtain a larger contact area, and were electropolished, but neither procedure improved the welding.

Grooves were ground in tungsten coupons, as shown in Figure 2, to attain greater contact area between the wire and the coupon, and to provide restraint on the wire. Welding was unsuccessful between electropolished tungsten wire and the grooved coupons even when tantalum foil interleaf was used.

Joints with a 56 percent efficiency were produced by using a grooved sonotrode tip with the electropolished wire and ground and electropolished tungsten coupons (without a groove). Attempts to improve the joint efficiency with the use of tantalum, columbium, and nickel-foil interleaves were unsuccessful.

4. Metallographic Evaluation of Welds

Test results on the welded junctures are summarized in Tables I and II. Physical properties of the materials used are listed in Tables VII, VIII, and IX. Typical types of specimen failures which occurred during tensile-shear testing are shown in Figure 3.

To prepare a specimen for metallographic evaluation, the following are important:

(1) The surface must be flat from edge to edge;

(2) The interface detail must be preserved;

(3) Minimum distortion and artifacts should be produced; and

(4) Etching distortion of the interface must be avoided.

The nature of ultrasonic welds between different metals or alloys is such that a distinct transition from one material to the other occurs at

the interface. The interfacial region may contain, among other factors, oxide or surface-film residues, residual surface irregularities and contamination, voids and non-bonded areas, diffusion zones, effects of local heating, and plastic flow. In the absence of interfering films and thermally induced structural changes, the interface apparently consists of a region of localized plastic flow.

The precise position of the interface of a good ultrasonic weld between similar metals generally cannot be detected in a polished specimen. Upon etching however, the interface may be revealed as a shallow groove similar in appearance to a high-angle grain boundary. The rate of etching attack at the interface is more rapid than that of the parent material. Prolonged etching, to delineate the structure of the weld members, greatly exaggerates the dimensions of the bond line.

In the case of dissimilar metal combinations, the interface can be detected after polishing by differences in surface relief, reflectivity, or color. Surface relief is produced by differing rates of metal removal during grinding and/or polishing, causing a difference in height at the junction. Combinations involving metals of different hardness and abrasiveness are particularly susceptible, which accounts for the shadow line which appears at the interface.

These aspects must be considered when preparing and examining weld specimens. Since the development of specific metallographic procedures was not within the scope of prescribed work, each metal combination was prepared by methods which, by experience or judgment, were considered likely to produce acceptable results. All of the specimens were, therefore, prepared by hand polishing, followed by chemical etching procedures where applicable.

Because of rapid interfacial attack in reagents by galvanic action, etching solutions and immersion times were carefully controlled to prevent excessive distortion of the interface. Etching was usually carried out in two stages. When etchants were available which would react with one member of the couple only, each component was etched individually. When double etching produced excessive interfacial attack, examination was carried out between each etching step. Photomicrographs were usually prepared after single etching, since the interface character was more faithfully preserved by this procedure. When suitable results were not achieved with standard etchants, the specimens were examined and photographed "as polished."

The photomicrographs of the weldments presented in the appendix are believed to represent the character of the ultrasonic bond. Summary descriptions of the photomicrographs are also presented, to aid in the interpretation of the weld structures. Sections of the 0.060-inch wire weldments were taken both longitudinal and transverse to the wire axis, and photographed at low (approximately 36X) and high (250X) magnifications. The fine-wire welds were sectioned in a transverse plane and photographed at 1000X.

a. Heavy-Wire (0.060-inch) Welds

1. The copper/copper (No. 1) and copper/silver (No. 45) junctions showed excellent bonding. The continuity of the interface is interrupted by plastic flow. The structure surrounding the interface of the copper/copper specimen (transverse section) is not resolvable except for a few recrystallized grains. Oxide residue interspersed with heavily worked material produced darker etching areas. The longitudinal section shows the transition from the weld region to the edge of the bond.

The copper/gold (No. 12) couple also exhibited good bonding. Comparison indicated that bonding is superior to that of the gold/copper weld (No. 2), wherein the lack of interpenetration might be improved through further investigations.

The copper/mild steel (No. 51) and copper/nickel (No. 26) photomicrographs showed continuous bond lines with negligible dispersion or interpenetration. Although the joints are satisfactory by tensile-shear strength criteria, bond quality could be improved.

The copper/stainless steel (No. 57) weld indicated that metallurgically inferior joints were obtained in this combination at the welding conditions used.

2. Gold

Deformation of the gold wire varied in the weldments of Combination Nos. 2, 13, 46, and 52. Bond quality paralleled the degree of wire deformation, although the tensile-shear strength of the joints approached or equalled the tensile strength of the wire. The gold/silver (No. 46) joint showed interpenetration and plastic turbulence at the interface. These interfacial effects provide adequate criteria for evaluating bond integrity of materials of similar hardness range. The gold/gold (No. 13) and gold/silver (No. 2) welds showed less wire deformation.

The gold/mild steel (No. 52) weld did not possess interfacial penetration characteristics due to hardness differences in the two materials. Local yielding of the softer gold establishes surface conformity and promotes physical adhesion of the surfaces. Prediction of bond quality in terms of joint strength is not possible for such combinations. Although tensile-shear tests indicate good joint efficiency, the character of the bond indicates some doubt that peel strength or direct tensile strength will be adequate.

3. Molybdenum

Good bonding was achieved between molybdenum and nickel (No. 28), 304 stainless steel (No. 59), and titanium sheet (No. 79). High interfacial temperatures occurred during welding, and resulted in partially recrystallized zones in nickel and titanium.

Areas of local turbulence and flow along the interface of the molybdenum/molybdenum (No. 19) specimen were evident, but the sample which was examined showed lack of bonding and/or separation.

4. Nickel

Both the nickel/nickel (No. 29) and nickel/mild steel (No. 53) welds did not bond uniformly. The nickel/nickel bond contained oxide residue, small voids at the interface, and local regions of partial recrystallization. Rapid etching of the heavily deformed regions of the surface grains produced the dark band along the nickel/mild steel interface.

The nickel/stainless steel (No. 60) joint showed good bonding without deep interpenetration. The nickel was partially recrystallized at the interface zone. Etching reduced the level of the nickel, and subsequently produced the shadow line shown in the higher magnification photomicrographs.

Good bonding is shown by the nickel/molybdenum combination (No. 20) but sub-interfacial cracks were observed in the molybdenum sheet. Modification of welding machine settings should prevent cracking of the molybdenum sheet.

The nickel/titanium (No. 80) interface exhibited microvoids and non-bonded areas. However, quality can be achieved in local regions of the interface, but additional work would be necessary to improve over-all weld quality. The nickel/rhenium couple (No. 39) also exhibited microvoids at the interface. The significance of the effect of interfacial microvoids on the properties of the joint depends upon the conditions of service exposure imposed on the weldment. No deleterious effect should be encountered in the proposed application, i.e., electrical contacts in vacuum or gas-filled electronic tubes.

Bonding appeared satisfactory in the nickel-tungsten (No. 86) specimen, although cracks in the tungsten sheet and interfacial voids occurred.

Mutual interpenetration of the contact surfaces indicated good bonding of the nickel/copper (No. 4) and nickel/tantalum (No. 70) specimens. Several microvoids at the interface of the nickel/tantalum couple were observed.

The interface of the nickel/silver (No. 47) specimen contained numerous small voids and several interface voids were observed in the nickel/gold sample (No. 14). Bonding was satisfactory in both cases, and the void areas may be eliminated by improved cleaning and/or surface preparation.

5. Rhenium

The rhenium wire used in these studies contained a large amount of internal porosity. Weld feasibility is shown by the photomicrographs of welds with nickel (No. 30), tantalum (No. 71), stainless steel (No. 61), and copper (No. 5). In all cases, the wire was imbedded into the sheet material.

Surface porosity of the rhenium wire produced the interface characteristics shown in the transverse section of the rhenium/nickel weld (No. 30). Intrusion of the voids by the nickel is apparent. A similar situation occurred in the section of the rhenium/stainless (No. 61) weld. However, in this case the void appears to be an intergranular crack. A non-bond region also appears.

Partial recrystallization and/or subgrain formation occurred in the weld zone of the rhenium/rhenium (No. 40) couple. Non-bonds and voids were observed at the interface, particularly in the center of the transverse section.

6. Silver

Results similar to gold-wire welds were achieved with the silver-wire combinations. The silver/gold (No. 15) and silver/copper (No. 6) couples showed an exceptional degree of interpenetration and turbulence. The interface and highly deformed and interspersed silver fragments were rapidly attacked by the etchant, and appeared dark. The silver/silver (No. 48) weld showed good bonding without appreciable interpenetration. Sections of the bond interface are outlined by oxide residues and preferential etch attack. Severe etch attack occurred at the interface of the silver/nickel (No. 31) weld. Therefore, it was examined "as polished," and good surface contact is indicated.

7. Low Carbon Steel

Excellent bonding of the mild steel/mild steel (No. 55) couple is displayed. Partial recrystallization and grain growth occurred across sections of the interface.

Gross deformation of the steel wire produced the spotty bonding observed in the mild steel/nickel (No. 32) specimen. The transverse section etched more rapidly than the longitudinal section, and the interface was more deeply attacked. The mild steel/gold (No. 16) combination contained extensive regions of non-bonding.

8. Type 304 Stainless Steel

Good bonding is shown by the stainless steel/rhenium (No. 41) weld. Interpenetration would not be expected in this combination because of

the difference in material hardness, and the high work-hardening capacity of rhenium. The appearance of the interface suggests that an alloy layer may have been produced.

The stainless steel/tantalum (No. 72) specimen exhibits a high degree of interpenetration, but the weld contains areas of separation, especially toward the perimeter of the bond.

Good bonding without weld defects is shown by the stainless steel/nickel (No. 33) and stainless steel/mild steel (No. 56) junctions. Recrystallization of the sheet in the region surrounding the weld occurred in both instances.

The surface of the stainless steel wire showed partial recrystallization in the stainless steel/stainless steel (No. 64) weld, but the interfacial area contained grain distortion and cold-working effects. Etching revealed a branching network of intercrystalline voids in the heavily worked regions of the interface and entire bond line. The rapid attack at the interface produced a groove or furrow which obscured microscopic detection, further complicating bond evaluation.

Deep etching of the interface also occurred in the stainless steel/titanium couple (No. 77). Recrystallization in the titanium surrounding the bond zone indicated that high temperatures developed during welding. The transverse section was apparently taken in a region of poor bonding. The longitudinal section shows the tapering recrystallized zone at the edge of the weld, and the surface interpenetration achieved.

9. Tantalum

Etching of the tantalum/tantalum (No. 73) specimen attacked the interface in a manner similar to the stainless steel/stainless steel weld (No. 64). The transverse section indicated local areas of high plastic turbulence and coalescence of interfacial material.

A distinct alloy layer was produced at the contact surfaces of the tantalum/titanium (No. 81) couple. The temperatures resulting from welding also produced a recrystallized zone in the titanium. Recrystallization temperatures for unalloyed titanium are between 1100° and 1350°F.

Satisfactory bonding was also achieved between tantalum and copper (No. 9). Differing rates of etch attack on the transverse and longitudinal section are indicated by the width of the dark band at the interface.

The tantalum/molybdenum (No. 23) junction was metallurgically unsatisfactory although joint efficiency was 100 percent. A change in welding conditions should produce uniform bonding for this combination. The tungsten cracked in the tantalum/tungsten (No. 89) junction. The tungsten sheet shows a delamination-type of failure beneath the bond interface, and separation of the titanium occurred only at the weld edge.

The tantalum/rhenium (No. 42) weld contained only scattered areas of bonding.

The tantalum/nickel (No. 34) specimen exhibited an exceptional degree of mutual interpenetration of the surfaces in local areas of the weld. Good interpenetration is also evident in the tantalum/stainless steel (No. 65) junction, but numerous microvoids and non-bonded regions indicate that additional work would be required to produce metallurgically sound welds in this combination.

10. Titanium

The titanium/copper (No. 10) junction showed good interpenetration and small wire-deformation. The wire was deeply imbedded in the copper sheet surface. The longitudinal section was accidentally tapered during preparation, and represents a diagonal section from edge to center of the weld.

Both the titanium/titanium (No. 82) and titanium/nickel (No. 35) welds showed considerable deformation of the wire. Flattening of the wire during welding produced a non-bonded edge defect. Complete recrystallization of the titanium wire, and recrystallization of the sheet along the interface have produced regions of structural continuity in the titanium/titanium couple. Rapid etching produced the dark line evident at the titanium/nickel interface.

11. Tungsten

Tungsten/titanium (No. 83) and tungsten/304 stainless steel (No. 67) specimens were successfully bonded, and the weld structures are similar to those obtained with molybdenum wire. The tungsten/tungsten specimen (No. 91) contained cracks in both wire and sheet, as well as cracks originating at the interface.

Bond quality of the tungsten/nickel (No. 36) and tungsten/tantalum (No. 75) specimens is difficult to judge because surface relief during polishing could not be avoided, and interface detail is partially obscured. However, the surfaces are in intimate contact, and no interface defects could be detected. The tungsten wire cracked during welding.

b. Fine-Wire Welds

Only those combinations of fine-wire weldments which could not be satisfactorily welded in the heavier gages were selected for metallographic preparation and examination. Each specimen was mounted in a plane transverse to the wire axis, and progressively ground until the weld area was intersected. Some of the combinations were subsequently rejected because of difficulties in locating the weld or preparing the specimen for examination. Stainless steel/copper (No. 8A) tungsten/molybdenum (No. 25A)

titanium/rhenium (No. 43A) copper/tantalum (No. 68A) and mild steel/copper (No. 7A) presented practical preparation difficulties that could not be resolved within the scope of this phase of the project. All the remaining combinations were examined and photographed at 1000X.

B. Electron-Tube Study

In this phase, weldments were completed with combinations of materials and configurations which are representative of those found in electron tube Types 6080WB, 5814WB, and 6205.

The ultrasonic welding of electron-tube mounts involves joining complex mechanical geometries. Areas presenting problems in ultrasonic welding are:

(1) The material combination;

(2) The geometrical configuration; and

(3) The accessibility of the sonotrode and anvil tips to the workpiece.

When joining dissimilar metals, for instance, welding is more difficult as the difference in the hardness of the materials becomes greater. Hardness may be accentuated by differences in geometries, such as welding wire to flat material. The influence of vibratory energy may tend to embed a hard wire into a soft flat material. Generally, geometrical configurations are not difficult to weld if the components being joined provide an adequate contact area at the junction to support the loads imposed during the formation of the weld.

The weld area accessibility of the sonotrode tip (the active welding tip) and the anvil can be a restrictive factor in the application of ultrasonic welding. As the welding tip is part of an acoustical system, its size and shape cannot be changed arbitrarily in a very great degree. The anvil tip must be essentially noncompliant to the imposed vibratory tones. Although the design of these parts was not reduced to precise engineering, experience provides an effective working tool without extensive research. Although the electron tube components in this program are not to be redesigned to facilitate ultrasonic welding, revision of the assembly sequence of the tubes may be used to assist in solving accessibility problems.

The design of tooling to effect component accessibility and the production of tube assemblies is scheduled under the next phase of the program. However, tooling used to demonstrate the satisfactory welding of the material combinations and geometrical configurations for the Type 6080WB was designed to overcome accessibility problems which will be encountered in making the complete tube mount. Parts for Types 5814WB and 6025 tubes were welded as separate assemblies or distorted to permit accessibility for simplified tooling, to determine the weldability of the components,

and to establish a basis for the design of production tooling. The final tube geometry, however, may limit the application of these data. The assembly sequences of these two electron tubes will be studied during the design of production tooling. The following discussions use the key numbers of the weld junctures established in the First Quarterly Progress Report.

The sonotrode tips on the 600-watt ultrasonic unit are held in place by a threaded stud. Tips with special geometries which require orientation to the direction of vibration and to anvil location must be machined in the proper relationship to the screw thread. This location is accomplished by screwing a blank tip onto the sonotrode reed, marking the blank for the proper location, and machining it. For quantities of tips, a master gage is substituted for the sonotrode reed. The master gage is occasionally designed as an arbor to hold the tip blank during subsequent machining operations.

The tips used in this study were not registered with respect to the screw thread when machined. Aluminum spacers (0.001 inch and 0.004 inch) were positioned between the sonotrode reed and the tip to locate the tip properly.

When a weld involves a small-diameter object such as wire, it is preferable to have the direction of vibration along the axis of the wire, as shown in Figure 4A, to restrict elastic deformation. If vibration is perpendicular to the axis of the wire, the wire will move together with the sonotrode tip either by deforming or rolling, making satisfactory welds difficult to achieve.

Successful ultrasonic welding of crossed wires is enhanced when the ratio of the wire diameters is very high, or when the wires are flattened before welding. Difficulties arise because the initial point contact between the two wires must progressively deform into some type of geometry, and there is no real weld interface to establish the necessary stress field which promotes a good metallurgical bond. In addition, one wire must be perpendicular to the direction of vibration.

When welding a thin, narrow flat ribbon to a wire, both the sonotrode tip and the anvil tip should be grooved to reduce component deformation.

When welding a wire to a thicker plate or in the middle of a large flat area, it is possible, depending upon the thickness of the plate, to weld through either the wire or the plate. Figure 4B shows a grooved sonotrode tip welding a wire to flat material held on a flat anvil surface. Figure 4C illustrates a spherical-radiused sonotrode tip welding through a flat plate to a wire nested in a grooved anvil tip. In both cases, the vibration is parallel to the axis of the wire.

Sonotrode tips and anvil tips used in this program were made from Type M2 (Allegheny-Ludlum DBL-2) heat-treated, untempered tool steel. This steel was used for tips which require silver brazing at assembly, since fully hardened steel softens very little at silver brazing temperatures of approximately 1200°F. Initially, the satisfactory performance of the M2 steel in welding a wide variety of materials (excluding high-temperature materials such as super alloys and refractory metals) resulted in an effective material standardization for most tool steel tip applications. It was subsequently replaced with Type L6 tool steel, as stated below.

1. <u>Welding the Type 6080WB Tube Mount Components</u>

All welds were made with the 600-watt welder, which produces an adequate power level for the combinations. Thus, welding difficulties encountered were not related to the available ultrasonic welding power.

The assembly sequence for this tube was refined further than that previously outlined (Second Quarterly Progress Report), and is shown in Table X in addition to the sonotrode tip and anvil geometries used for each material combination. Figures 5 and 6 illustrate these geometries.

Type L6 (Allegheny-Ludlum Tioga, Carpenter RDS), a low-alloy special purpose steel of high-nickel content for increased toughness and hardness, replaced the M2 steel in the sonotrode tips. Several of the M2 tips had broken across the screw thread connection, as shown in Figure 7A, due to the brittleness resulting from the heat treatment and from the stresses imposed by the off-set tip contact. No failures have occurred under the same amount of use using screw-on tips made from Type L6 tool steel.

The anvil tips were designed to fit previously used copper anvil base configurations which were available from stock. One style used a round brazed-on anvil tip; the other, a bolted-on rectangular anvil tip.

The anvil tip designated as A1 failed in use, as shown in Figure 7B. After the steel was changed from Type M2 to Type L6, no further breakage occurred.

The anvil tip designated as A2 failed in use, as shown in Figure 7C. This tip requires redesign to supply greater strength across the critical section. A change to material with greater toughness will also provide greater resistance to failure.

The anvil tip shown in Figure 8A was made to provide a support for welds in attaching the stem assembly to the mount assembly. The shape was designed to provide clearance for all welds made in this general tube area, but proved unsuccessful because the projection was too long. At the power level employed, the extension vibrated together with the sonotrode tip, and was ineffective.

A second anvil tip, shown in Figure 8B, was made with an extension somewhat less than the one previously designed. This tip was altogether satisfactory in producing sound welds, but did not provide adequate clearance for all of the tube components during the assembly operation.

The anvil tip was then modified as shown in Figure 8C to give the necessary clearance. After this modification, the tip exhibited some torsional compliance and reduced effectiveness. This tip can be readily revised to eliminate the torsional compliance and provide the required clearance.

The following was noted when specific junctions were welded:

Key 1 Cathode Tab to Cathode Sleeve

The machine settings had to be established with some care to avoid cutting through the cathode tab.

The sonotrode tip was shaped to make a band-like weld across the cathode tab. The edges of the tip were rounded to avoid cutting.

The weld must be made approximately 1/32 inch back from the end of the cathode sleeve to prevent the cathode sleeve from moving under the welding tip. If a weld is required closer to the end of the sleeve, the cathode sleeve will require clamping.

Key 2 Cathode Tab to Itself

The cathode tab is threaded through the top spacer and welded to itself on top of the weld previously made between the cathode tab and cathode sleeve.

Somewhat higher power was required to make this weld than was required to make the weld between the cathode tab and the cathode sleeve, increasing somewhat the possibility of cutting the cathode tab.

Key 6 Grid Eyelet to Grid

See Key 7 for explanation.

Key 7 Anode Eyelet to Anode Support

Because of the shape of the tooling, the resulting deformation of the eyelets is different from that attained in resistance welding, as illustrated in Figure 9. Welds are satisfactory.

Key 9 Heater to Heater Connector, Heater Sleeve

Welds were made with nickel sleeves and heater wires to the heater connector in one step, rather than welding the nickel sleeves to the heater wires before joining to the heater connector. Two such wire assemblies were joined simultaneously to the heater connector.

A microphotograph of this weld is shown in Figure 10. Bonding occurred between the bottom of the tungsten wire and the nickel sleeve. The bonding occurring through the nickel sleeve to the heater connector adds mechanical strength to the joint.

Key 10 Grid Radiator to Grid

The grid radiator is made from carbonized nickel. The carbon coating inhibits welding; the bonds produced had somewhat less mechanical strength than those obtained between bare nickel and copper. However, in the final tube assembly this joint cannot be made by ultrasonic welding because the weld area is not accessible to the welding tips.

Key 15 Snubbers to Snubber Supports

The snubber is made from Inconel hard-temper, and the snubber support is made from half-hard nickel. The hardness difference of the components made welding very difficult. The hard Inconel embedded into the nickel wire. A nickel foil interleaf did not improve weldability.

Key 17 Getters to Snubber Supports

This configuration is a crossed-wire weld. The difficulties associated with cross-wire welds are described in the introductory material to Section B, Electron-Tube Study.

2. Welding Junctions for Type 5814WB Electron Tube

Tooling used is listed in Table XI and is illustrated in Figures 5 and 6. The following was noted when welding specific junctions.

Key 1 Cathode Tab to Cathode

The cathode was nested in a groove in the anvil tip. A small mandrel was put inside the cathode to prevent the tube from collapsing during welding. Welding was altogether successful.

Key 2A Stem Lead to Plate

The stem lead was deformed and embedded into the plate during welding. Some difficulty may be encountered in a production weld because of the limited area available for the joint.

Key 3B Heater Connector to Heater

This is a crossed-wire weld between tungsten and nichrome. No background effort in the study provided a basis for ultrasonically welding this geometric or material combination. A junction that would provide electrical contact was attained, but mechanical strength was marginal.

Key 4 Heater to Stem

This junction is formed between a tungsten wire and a nickel ribbon. The hard tungsten wire embedded into the softer nickel surface. Although a bond was formed and electrical conductivity obtained, the mechanical strength of this joint was marginal. Harder nickel will improve weldability.

Superior mechanical strength could be obtained by the use of a nickel sleeve as in the same type of junction on the Type 6080WB electron tube, or by an overlay of a thin nickel tab.

Key 5 Getter to Plate

A strong joint was produced, but the copper-flashed steel wire from the getter embedded somewhat deeply into the alclad iron plate. Little area of contact between these parts is available in the production junctures.

3. Welding Junctions for Type 6205 Electron Tube

Tooling is listed in Table XII and is illustrated in Figures 11 and 12. The following was noted when specific junctions were welded:

Key 3 Stem Shield to Bottom Shield

This weld was made using a standard 2-inch spherical-radius sonotrode tip. Production tooling should use a 0.25 to 0.50 spherical radius for a smaller weld area and greater strength.

Key 4A Grid Connector to #2 Grid

See Key 4B for explanation.

Key 4B Grid Connector to #3 Grid

These welds were made at high power and high clamping force with the 100-watt welder. With this combination of settings, tuning the power source to the proper resonance setting becomes somewhat more important.

Key 6 Bottom Shield to Stem Lead

Higher strengths were obtained in this junction when using a spherical-radius sonotrode tip and a grooved anvil to hold the wire than when a grooved sonotrode tip and a flat anvil tip were used. Welds were satisfactory.

Key 7 Heater to Heater Connector

This junction is formed between a tungsten wire and a nickel ribbon. The hard tungsten wire embedded into the softer nickel surface. Although a bond was formed and electrical conductivity obtained, improved mechanical strength is necessary and this may be obtained by the use of a nickel sleeve as in the same type of junction on the Type 6080WB electron tube, or by an overlay of a thin nickel tab.

Key 10 Getter to Top Shield

The getter is a circular piece with a channel cross section filled with oxide. The getter was cut and flattened and in this form welded satisfactorily to the top shield. When this weld is made in the standard geometry, deformation of the getter occurs, resulting in expulsion of some of the oxide.

II. CONCLUSIONS

Junctions in almost all of the desired combinations were successfully effected. The importance of surface condition and contamination in some materials, such as tungsten and molybdenum, is significant.

With the exception of crossed-wire weld configurations, virtually all the required junctions in the three specific electron tubes can be ultrasonically welded. An assembly sequence was established for one of the electron tubes to minimize accessibility problems.

III. PROGRAM FOR THE NEXT REPORTING PERIOD

Sample welds will be made of all the successfully welded combinations for exposure to the shock and vibration tests previously established.

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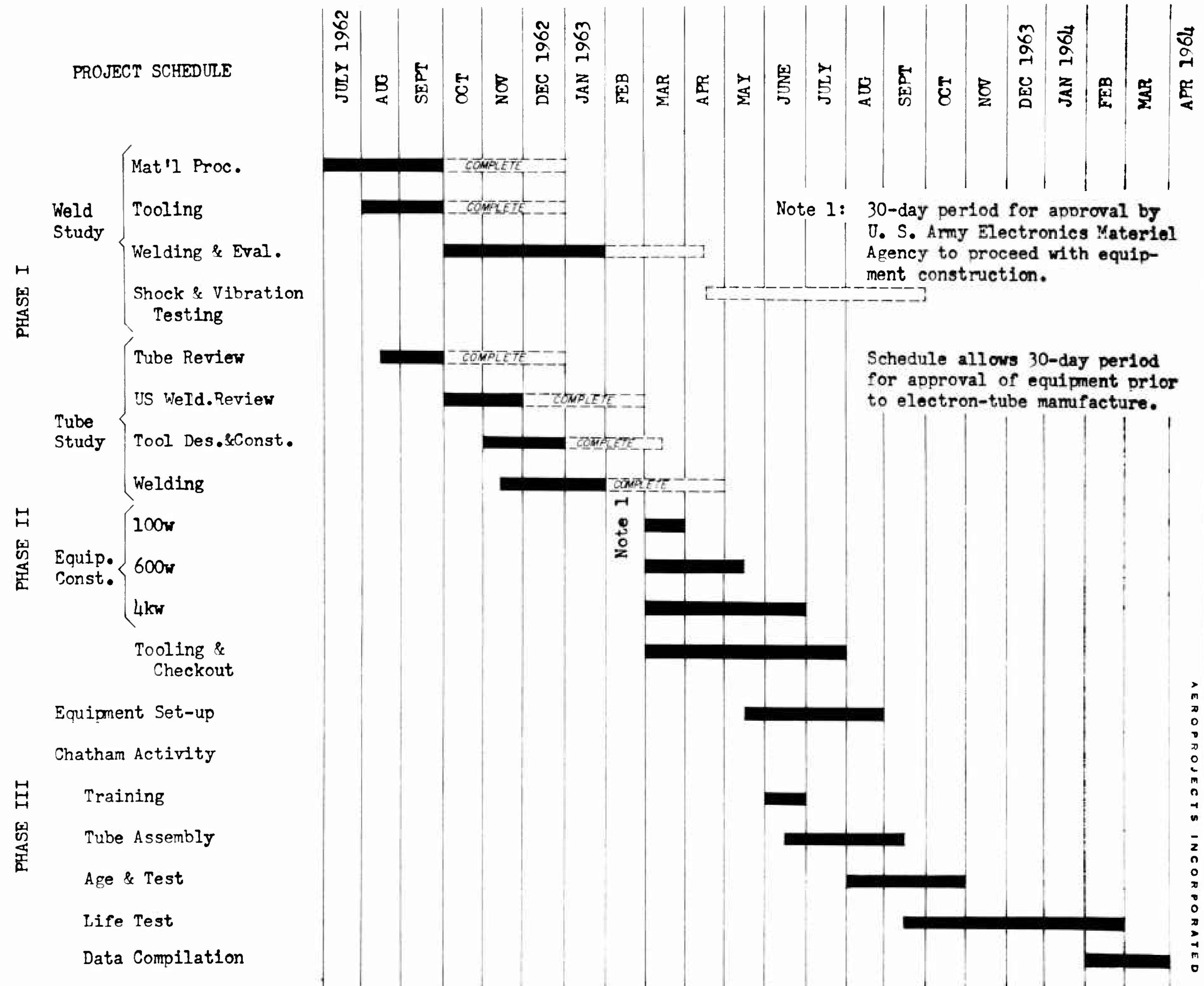

PROJECT SCHEDULE
JULY 1962
AUG
SEPT
OCT
NOV
DEC 1962
JAN 1963
FEB
MAR
APR
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC 1963
JAN 1964
FEB
MAR
APR 1964
PHASE I
Weld Study
Mat'l Proc.
Tooling
Welding & Eval.
Shock & Vibration Testing
Tube Study
Tube Review
US Weld.Review
Tool Des.&Const.
Welding
PHASE II
Equip. Const.
100w
600w
4kw
Tooling & Checkout
PHASE III
Equipment Set-up
Chatham Activity
Training
Tube Assembly
Age & Test
Life Test
Data Compilation
COMPLETE
COMPLETE
COMPLETE
COMPLETE
COMPLETE
COMPLETE
Note 1
Note 1: 30-day period for approval by U. S. Army Electronics Materiel Agency to proceed with equipment construction.
Schedule allows 30-day period for approval of equipment prior to electron-tube manufacture.
AEROPROJECTS INCORPORATED

TECHNICAL MAN-HOURS

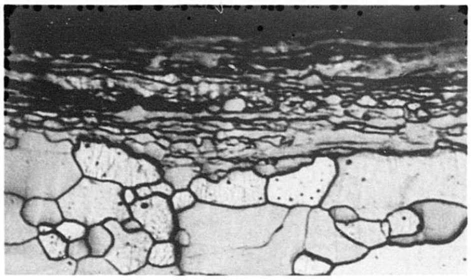
EXPENDED DURING THIS REPORT PERIOD

Name	Project Position	Hours Expended This Report Period
W. N. Rosenberg	Project Supervisor	85
J. Koziarski	Director Welding Lab	99
J. G. Thomas	Metallurgist	319
G. Sekula	Junior Engineer	343
A. L. Fuchs	Chief Design Engineer	32
C. DePrisco	Chief Electronics Engineer	2
W. B. Devine	Director of Publications	63
N. Maropis	Physicist	5

VISITATIONS DURING THIS REPORT PERIOD

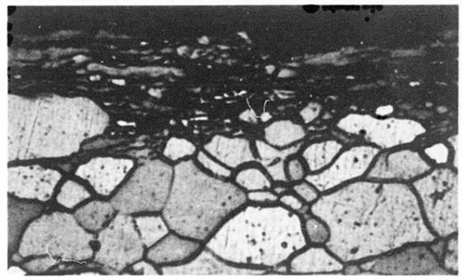
Date	Visit	Purpose of Visit
1/23/63	W. N. Rosenberg visited Mr. H. Shienbloom, U. S. Army Electronics Materiel Agency, 225 S. Eighteenth Street, Philadelphia, Pennsylvania	Review Progress Report and technical status of program.

Aeroprojects Mo Coupon



Depth of Surface Contamination
0.0005 to .00015 inch

Chatham Mo Coupon



Depth of Surface Contamination
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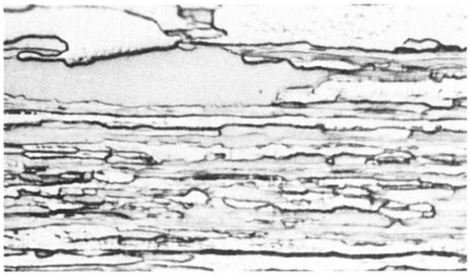
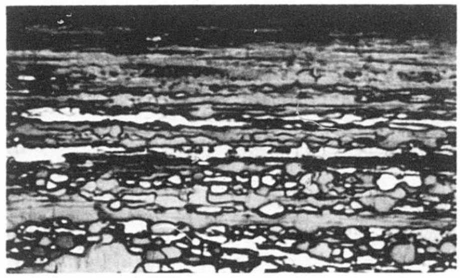
Aeroprojects Mo Wire



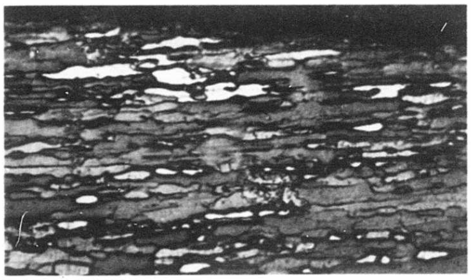
Depth of Surface Contamination
up to 0.006 inch
Coarse Grain of the Core

Chatham Dull Mo Wire



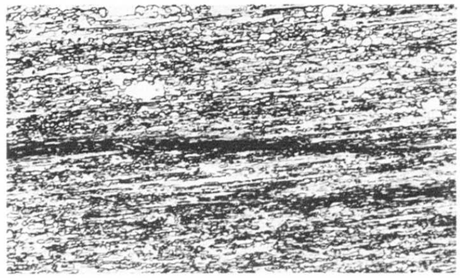
Depth of Surface Contamination
about 0.002 inch
Fine structure of the Core

Chatham Bright Mo Wire



No Surface Contamination
Fine grain structure of the core. Twisted

* Chatham Bright Mo Wire



Longitudinal Internal Cracks
Twisted

Figure 1

MOLYBDENUM RECRYSTALLIZATION STUDIES

All specimens recrystallized in dry Argon atmosphere for ten minutes at 2450°F except * this specimen.

All photographs: Etchant: KOH + $K_3Fe(CN)_6$
Magnification: 500X

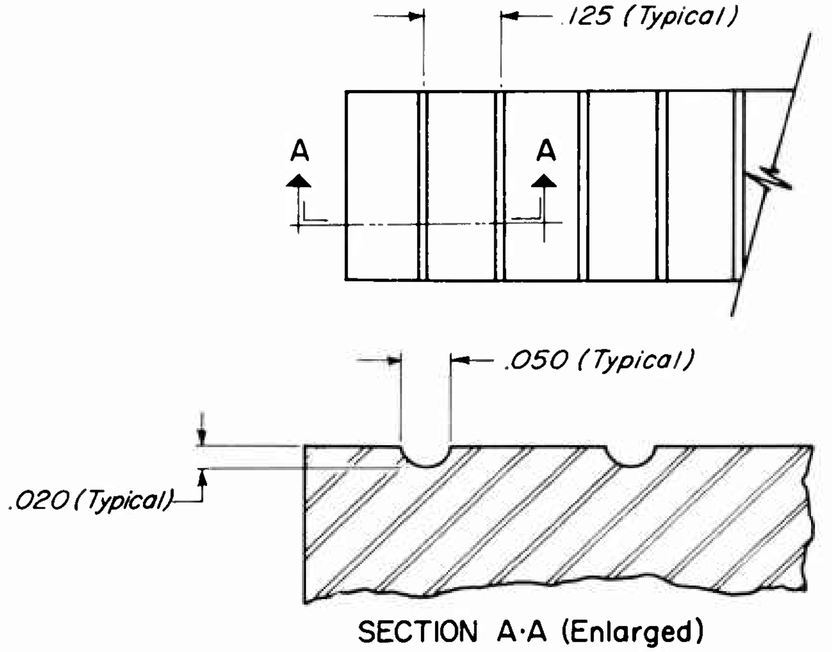


Figure 2

TUNGSTEN COUPON WITH GROOVES

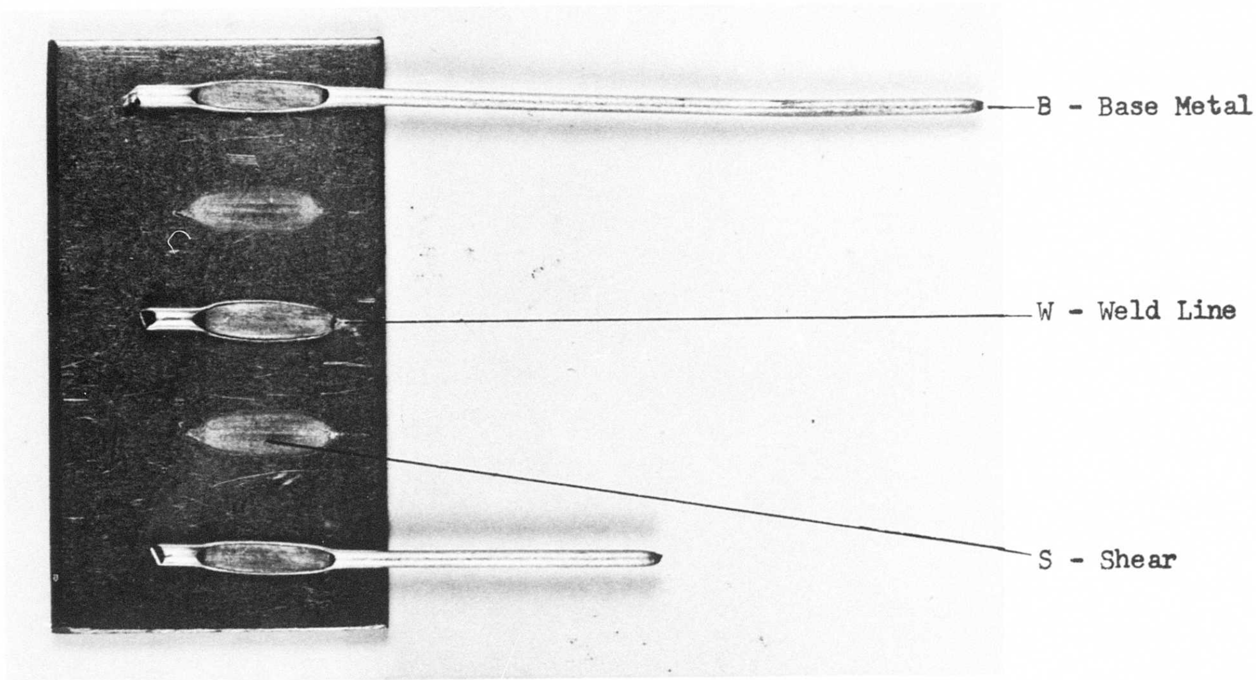
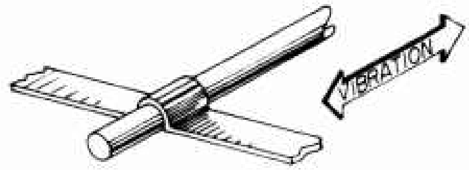
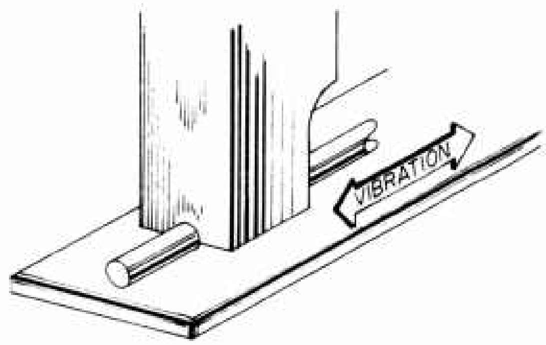


Figure 3

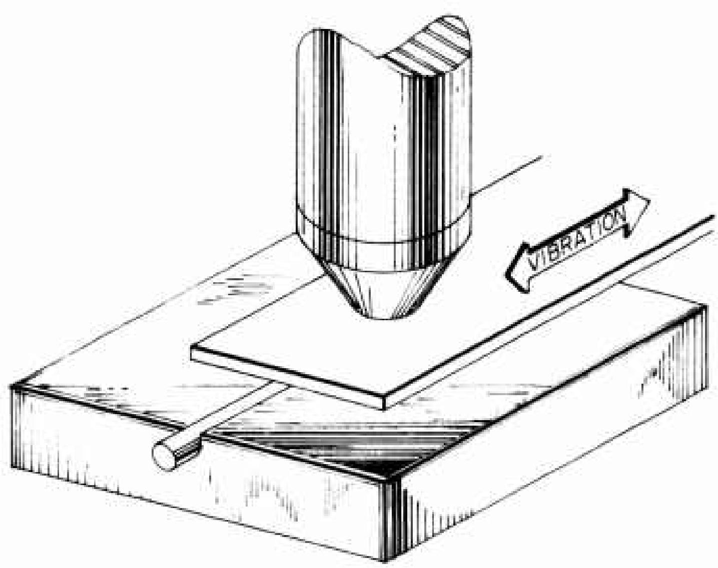
TYPICAL TYPES OF FAILURES DURING
TENSILE-SHEAR TESTING OF WELDS



A



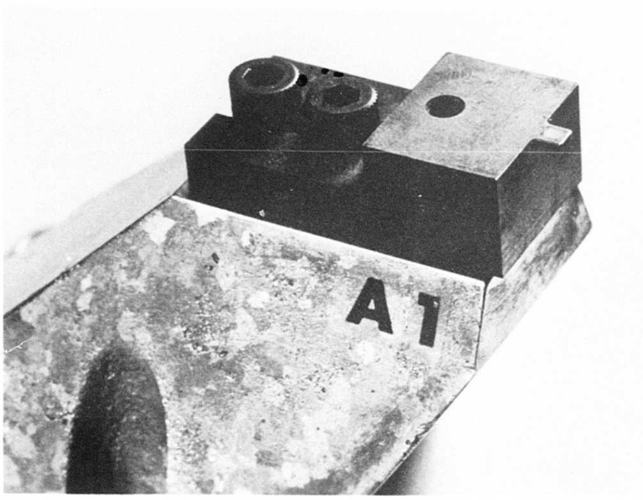
B

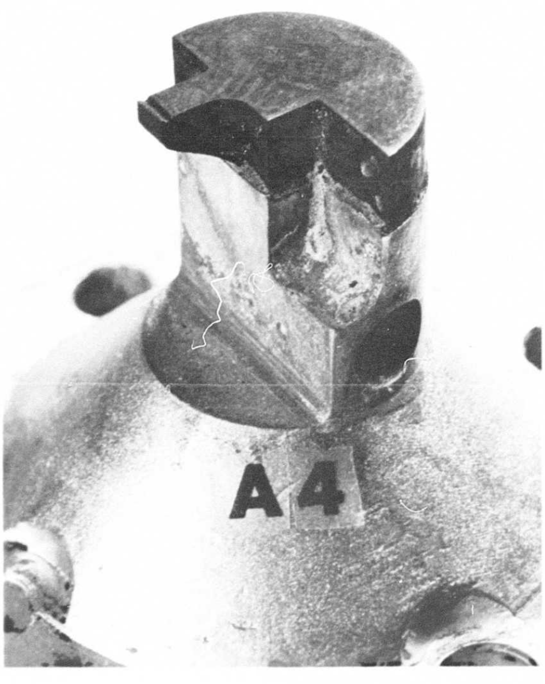


C

Figure 4

DIRECTION OF VIBRATION AND TIP GEOMETRIES IN ULTRASONIC WELDING





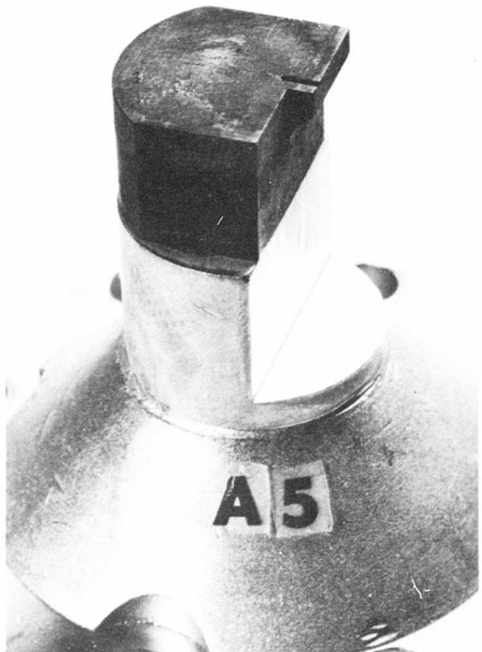


Figure 5

ANVILS - TYPES 6080WB AND 5814WD
ELECTRON TUBES

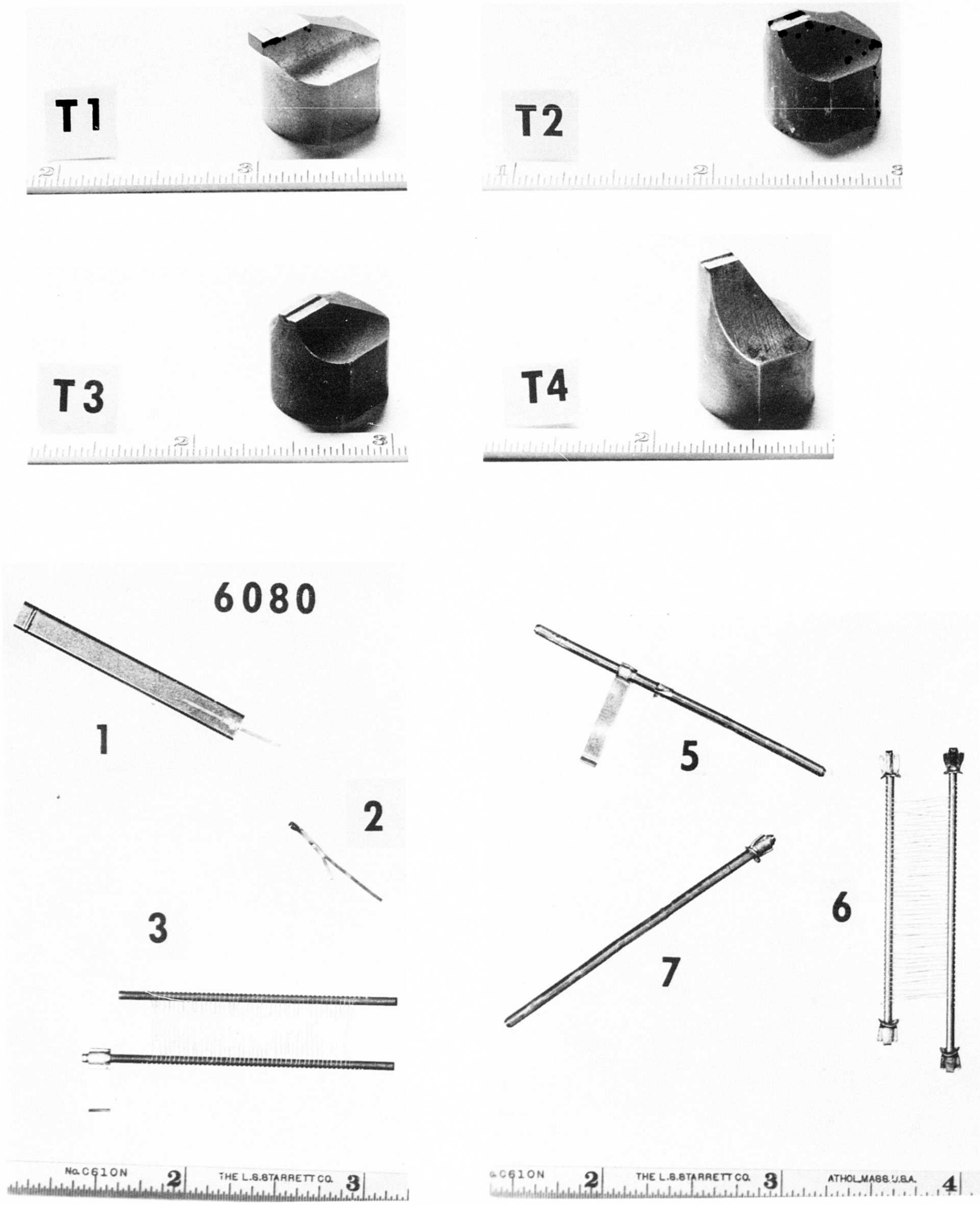
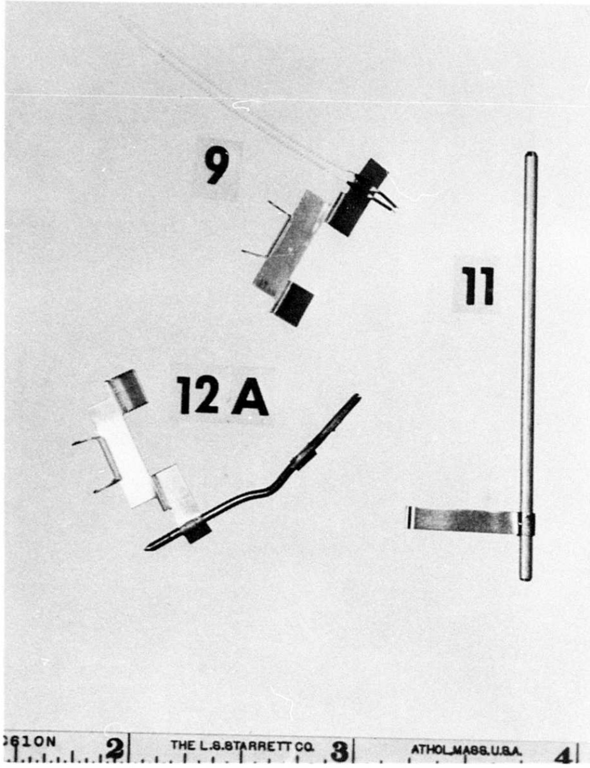
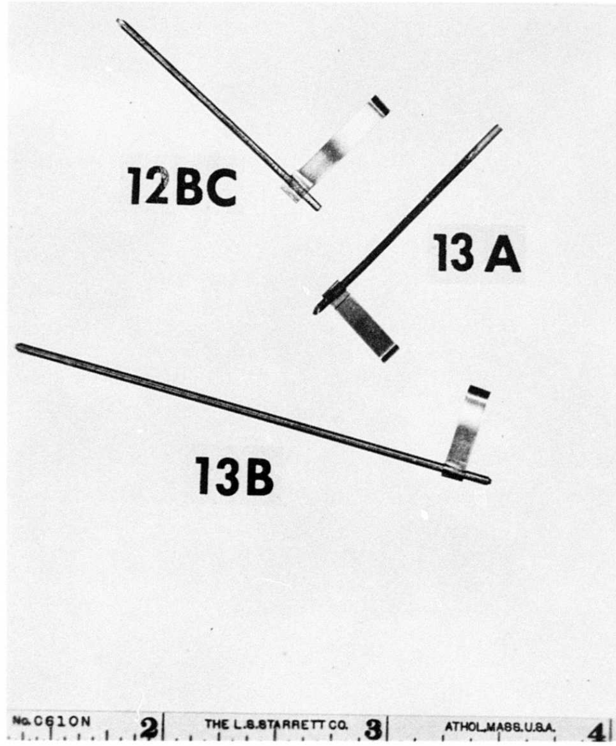


Figure 6

TOP: SONOTRODE TIPS - TYPES 6080WB AND 5814WB ELECTRON TUBES

BOTTOM: WELDMENTS TYPE 6080WB ELECTRON TUBE





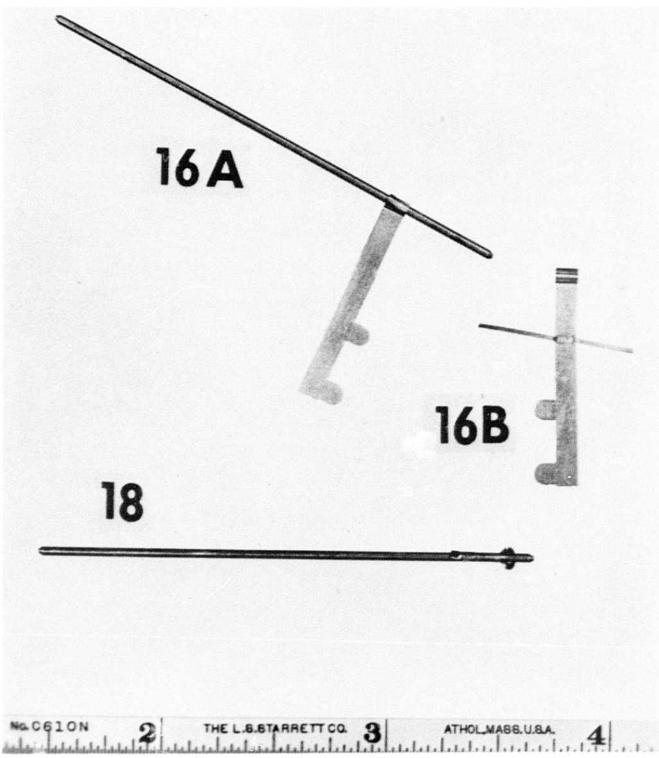
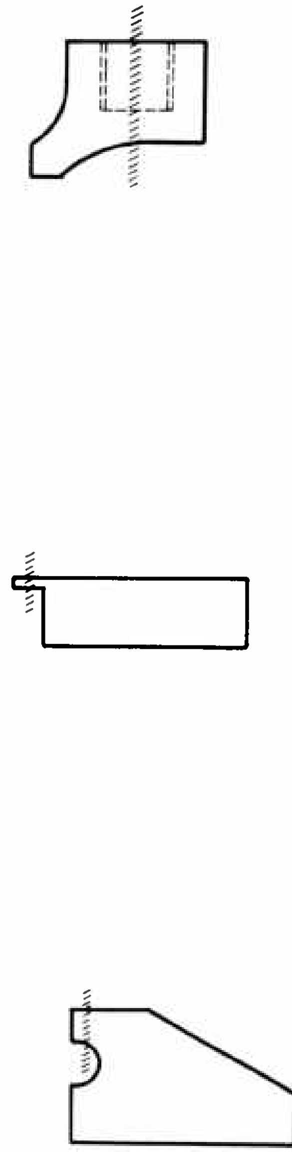


Figure 6A

WELDMENTS - TYPE 6080WB ELECTRON TUBE



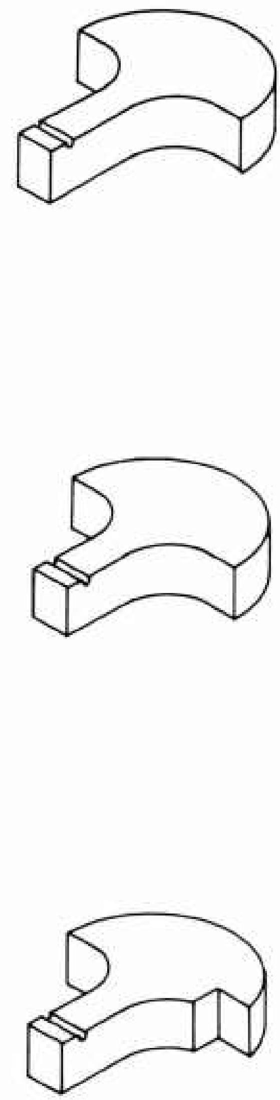
A Sonotrode Tip

B Anvil Tip

C Anvil Tip

Figure 7

AREAS IN SONOTRODE AND ANVIL TIPS
WHERE INITIAL FAILURES OCCURRED



A

B

C

Figure 8

ANVIL TIP DESIGNS

A - Resistance Weld

B - Ultrasonic Weld

Figure 9

COMPARISON OF RESISTANCE AND ULTRASONIC WELDS
ANODE EYELET TO ANODE SUPPORT TYPE 6080WB ELECTRON TUBE

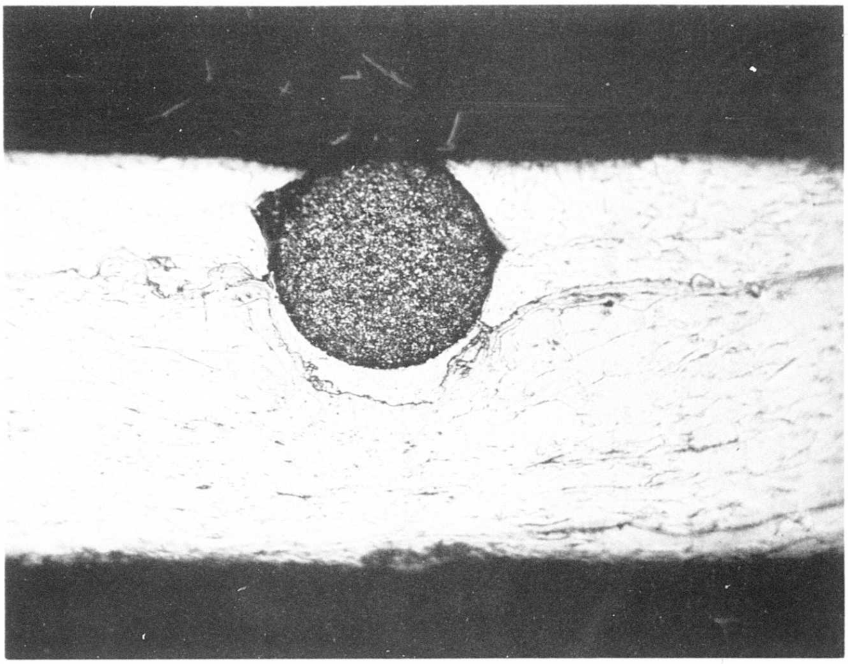


Figure 10

PHOTOMICROGRAPH OF TUNGSTEN WIRE/NICKEL SLEEVE/
NICKEL-PLATED STEEL COMPOSITE WELD

Magnification: 300X
Etchant: KOH + $K_3Fe(CN)_6$

The nickel sleeve has been severed by the deformation accompanying welding. Bonding has occurred at the base of the tungsten wire only, where the wire is embedded in the nickel-plated steel strip. Note the high degree of turbulence and interpenetration of the faying surfaces of nickel and nickel-plate. The flattening of the nickel sleeve has permitted bonding of the contact surfaces (ID tube surface) and imposes a mechanical "crimping" effect on the wire which probably contributes significantly to its peel resistance.

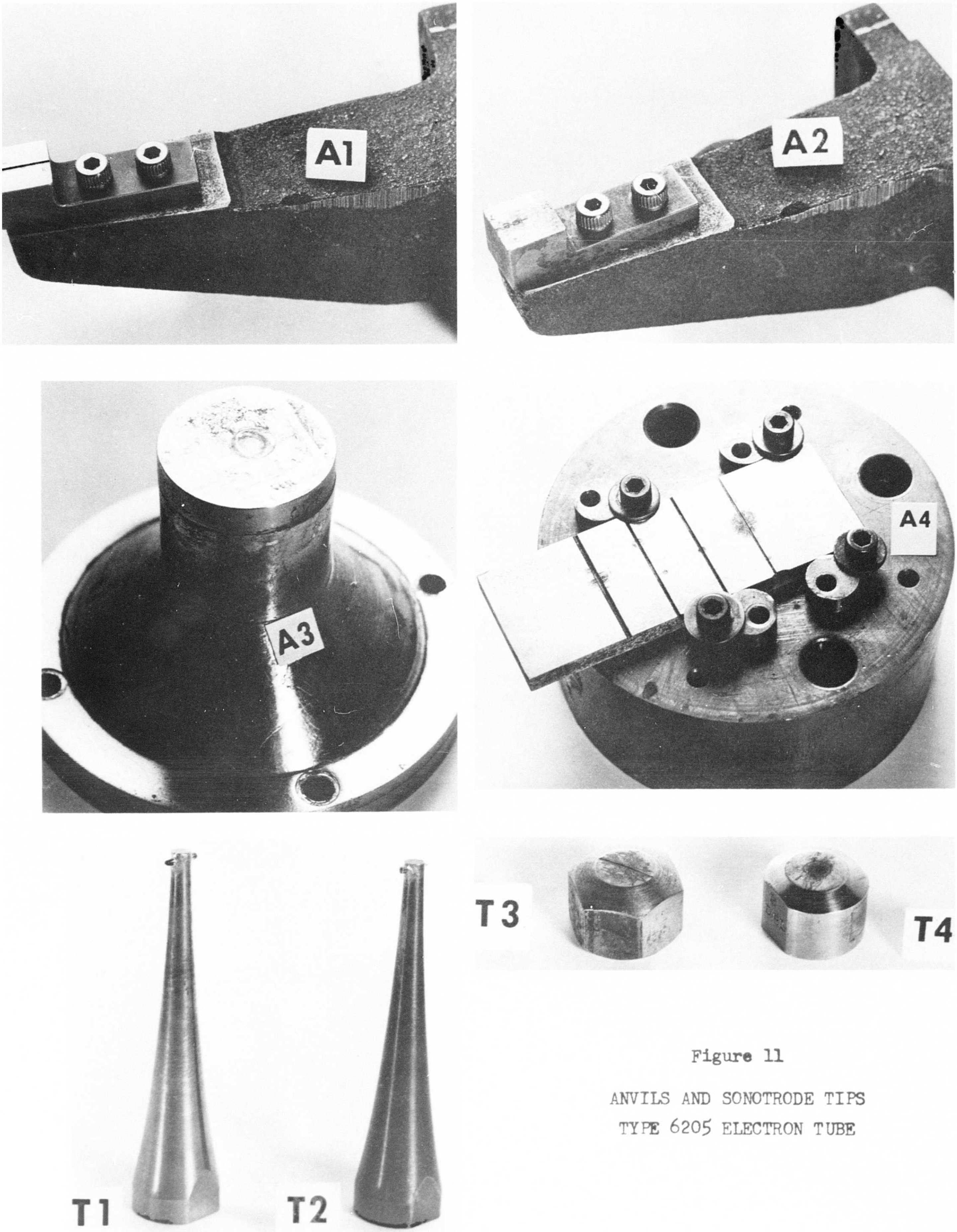


Figure 11

ANVILS AND SONOTRODE TIPS
TYPE 6205 ELECTRON TUBE

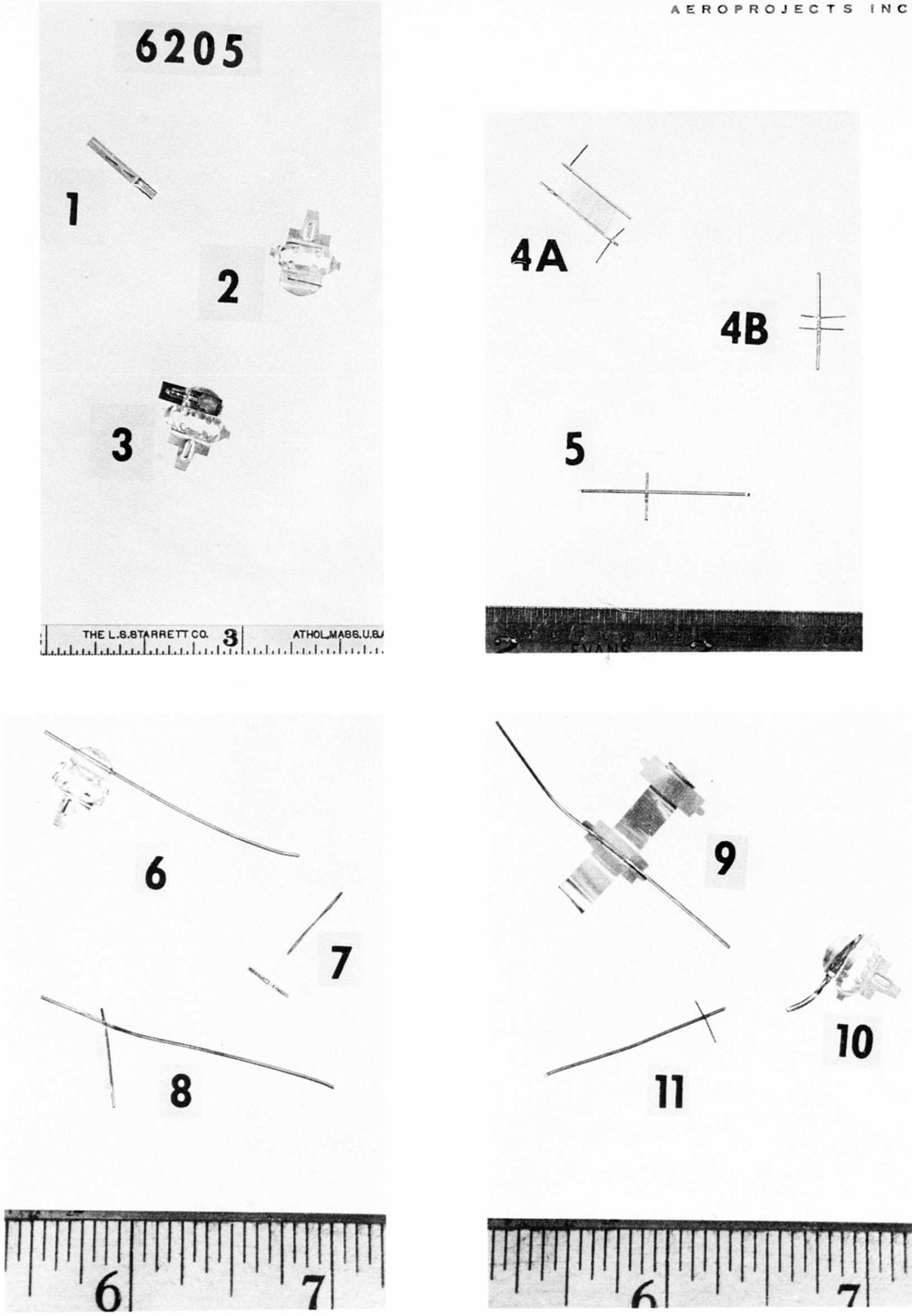
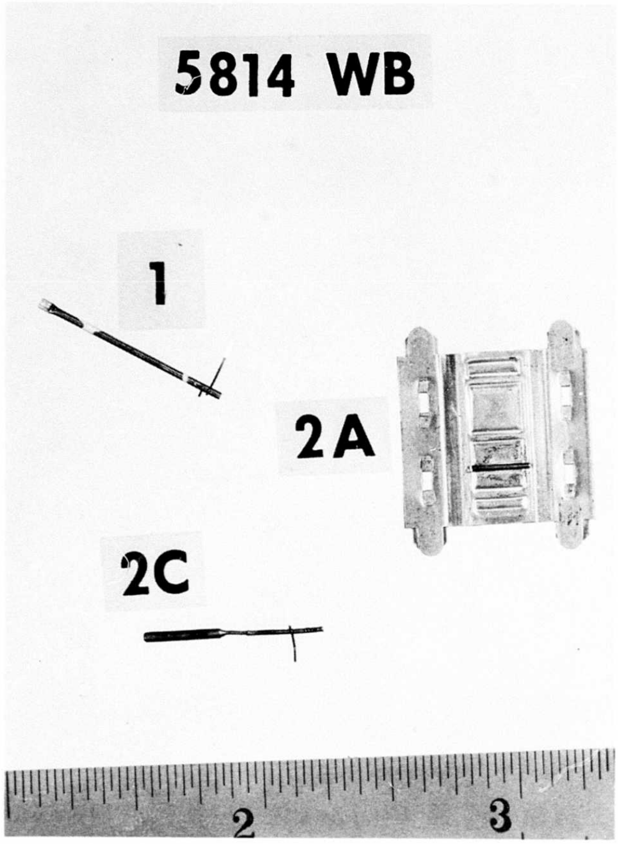
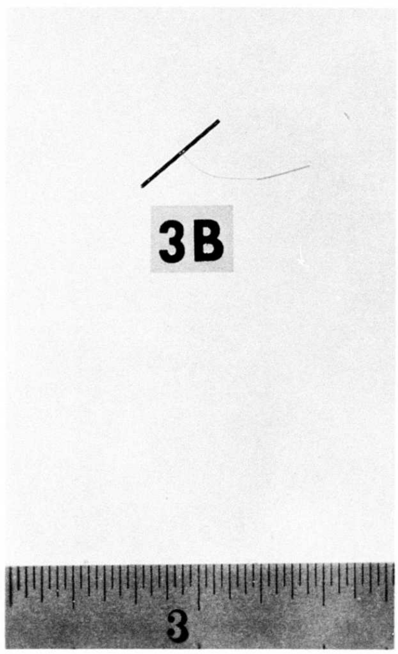


Figure 12

WELDMENTS - TYPE 6205 ELECTRON TUBE





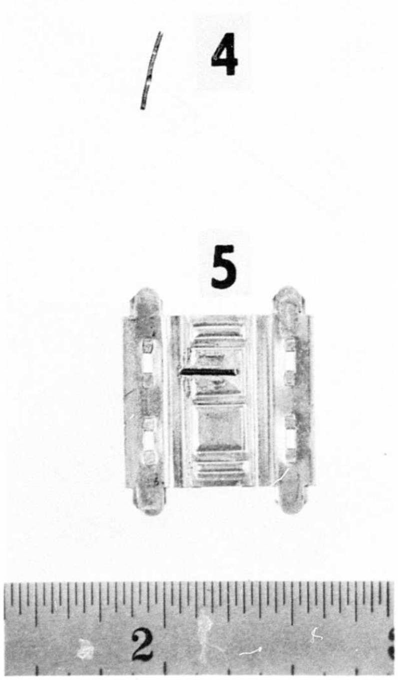


Figure 13

WELDMENTS - TYPE 5814WB
ELECTRON TUBE

Table I

TEST RESULTS OF HEAVY-WIRE-TO-COUPON JUNCTURES

(All Welding Conducted on 4KW Spot-Welder)

Weld Combination Materials: Coupon	Combination No.	Wire	Joint Efficiency (percent)#	Tensile-Shear Strengths: Base Wire* (lbs)(2)	Tensile-Shear Strengths: Welded Wire* (lbs)(1)	Variation**	Welding Comments
	1	Copper	100+	114	118	0.101	b,j
	2	Gold	100+	53	55	0.019	k,m
	3	Molybdenum					
	4	Nickel	100+	159	160	0.088	b,j
	5	Rhenium	87	360	313	0.15	o
Copper	6	Silver	100+	76	80	0.05	c,i,m
	7	Mild S					
	8	SS					
	9	Tantalum	91	151	138	0.32	h,o
	10	Titanium	100+	256	264	0.95	c,u,x
	11	Tungsten					
	12	Copper	100+	114	119	0	b,g
	13	Gold	100+	53	54	0.019	c
Gold	14	Nickel	95	159	152	0.223	p
	15	Silver	100+	76	79	0	b,g,k,m
	16	Mild S	97	157	153	0.026	p
	17	SS					
	18	Copper					
	19	Molybdenum***	86	285	244	0.098	u
	20	"A" Nickel	100	159	164	0.012	t
Molybdenum	21	Rhenium					
	22	SS	40	268	107	0.439	u,r
	23	Tantalum	100	151	153	0.0457	t
	24	Titanium					
	25	Tungsten					
	26	Copper	91	114	109	0.0036	c,m
	27	Gold	100	53	54	0.0185	c,m
	28	Molybdenum	88	386	343	0.2186	c,hh
	29	Nickel	99	159	158.7	0.057	c,v

Molybdenum	20	"A" Nickel	100	159	164	0.012	t
	21	Rhenium					
	22	SS	40	268	107	0.439	u,r
	23	Tantalum	100	151	153	0.0457	t
	24	Titanium					
	25	Tungsten					
"A" Nickel	26	Copper	91	114	109	0.0036	c,m
	27	Gold	100	53	54	0.0185	c,m
	28	Molybdenum	88	386	343	0.2186	c,hh
	29	Nickel	99	159	158.7	0.057	c,v
	30	Rhenium	100+	360	370	0.0567	b
	31	Silver	76	76	58	0.086	m
	32	Mild S	100	157	157	0.0312	b,v
	33	SS	92	268	248	0.0645	c
	34	Tantalum	94	151	142	0.035	b
	35	Titanium	94	256	242	0.045	c,m
	36	Tungsten***	85	579	491.7	0.132	ee,ff
Rhenium	37	Copper					
	38	Molybdenum					
	39	"A" Nickel	78	159	124	0.217	d,g,gg,m
	40	Rhenium	74	360	268	0.459	s,ii
	41	SS	94	268	253	0.0276	c
	42	Tantalum	100	151	150	0.04	c,u
	43	Titanium					
	44	Tungsten					
Silver	45	Copper	95	114	107.7	0.009	b,e,s
	46	Gold	100	53	54	0	a,m
	47	"A" Nickel	90	159	152.3	0.0065	b,e,q,z
	48	Silver	93	76	73.7	0.0135	b,e
	49	Mild S	61	157	96	0.845	oo
	50	SS					
Mild Steel	51	Copper	96	114	110	0.1	c
	52	Gold	86	53	46	0.108	s
	53	"A" Nickel	73	159	116	0.0603	l
	54	Silver					
	55	Mild Steel	100	157	157	0.0317	b
	56	SS	95	268	255	0.0231	b
Stainless Steel	57	Copper	55	114	63	0.526	d,s
	58	Gold					
	59	Molybdenum	93	540	505	0.1564	c,s,ll
	60	"A" Nickel	97	159	155	0.006	r,s
	61	Rhenium	100+	360	364	0.033	b
	62	Silver					
	63	Mild Steel	100+	157	160	0	b,g
	64	SS	100+	268	280	0.05	a
	65	Tantalum	100+	145	152	0.052	a
	66	Titanium					
	67	Tungsten	83	660	480	0.385	jj,kk

2

Table I (Concluded)

Weld Combination Materials			Joint	Tensile-Shear Strengths			
Coupon	Combination No.	Wire	Efficiency (percent)#	Base Wire* (lbs)(2)	Welded Wire* (lbs)(1)	Variation**	Welding Comments
Tantalum	68	Copper					
	69	Molybdenum					
	70	"A" Nickel	98	159	155.8	0.025	s,aa,bb,cc
	71	Rhenium	100	151	150	0.04	c,u
	72	SS	89	268	239	0.625	d,f,h,s
	73	Tantalum	100	151	161.3	0.062	aa,bb,cc,dd
	74	Titanium	73	256	187	0.428	u,r
	75	Tungsten***	72	579	431	0.498	f,s
Titanium	76	Rhenium	100	343	343	0.0758	c
	77	SS	100+	268	275	0.0072	d,p
	78	Copper					
	79	Molybdenum	93	540	500	0.25	d,f,h,ll
	80	"A" Nickel	94	159	148.7	0.08	d,m,n,v
	81	Tantalum	100	151	150	0.02	c,p
	82	Titanium	100	256	257	0.0194	c,u,m,n
	83	Tungsten***	72	579	503	0.068	c,ll
Tungsten	84	Copper					
	85	Molybdenum					
	86	"A" Nickel***	100+	159	165	0	b,w
	87	Rhenium					
	88	SS ***	93	268	250	0.096	c,w
	89	Tantalum***	97	151	145	0.041	d,w
	90	Titanium					
	91	Tungsten***	56	579	327	0.1987	mm,nn

All combinations were welded on 4-kw spot welder.

* Average of three specimens.

** Variation = $\frac{\text{highest shear-strength value} - \text{lowest shear-strength value}}{\text{average of individual shear strengths}}$

*** After surface preparation of base wire and/or coupon.

$\# = \frac{\text{Col}(1)}{\text{Col}(2)} \times 100$

Unrecorded efficiencies indicate minimal or inconsistent welds

\+ After efficiency means higher average than unwelded wire.

SS is AISI stainless steel Type 304

91	Tungsten***	56	579	327	0.1987	mm,nn

All combinations were welded on 4-kw spot welder.

* Average of three specimens.

** Variation = $\frac{\text{highest shear-strength value - lowest shear-strength value}}{\text{average of individual shear strengths}}$

*** After surface preparation of base wire and/or coupon.

\# = $\frac{\text{Col(1)}}{\text{Col(2)}}$ x 100

Unrecorded efficiencies indicate minimal or inconsistent welds

\+ After efficiency means higher average than unwelded wire.

SS is AISI stainless steel Type 304

Mild Steel is AISI 1010

WELDING COMMENTS

a) Excellent weldability.
b) Very good weldability.
c) Good weldability.
d) Satisfactory weldability.
e) Low rate of variation.
f) High rate of variation.
g) No variation.
h) Improved variation possible through further study.
i) Acceptable amount of wire deformation.
j) Small amount of wire deformation.
k) Wire deformation could be decreased by manipulation of welding parameters.
l) High power and grooved tip should be used to decrease wire deformation and notch and to increase tensile-shear.
m) Use of grooved tip would reduce wire deformation.
n) Larger tip radius would decrease wire deformation.
o) Etching and/or flattening of wire might improve joint.
p) Wire required flattening before welding.
q) To remove strain hardening, flattened wire had to be stress relieved annealed before welding.
r) No reliable weld possible with spherical-radius tip.
s) Grooved tip would improve weldability.
t) Electroetched sheet and grooved tip produce good weldability.
u) Grooved tip mandatory.
v) Larger spherical-tip radius or grooved tip would decrease weld-line notch.
w) Grinding and electroetching of sheet and use of grooved tip are mandatory.
x) Welding without grooved tip produces cutting through plate.
y) Abraded sheet and wire offers very good weldability.
z) Excessive imbedding proved objectionable. Flattened wire could be used on thin sheet.
aa) Size of details (small parts) may cause resonance problems.
bb) Either damping or changing the natural frequency, or both, would help.
cc) Better joint is produced without removal of surface film from tab.
dd) Very good weldability without abrading sheet or wire.
ee) Removal of surface film needed to improve variation and reduce wire cracking.
ff) Grooved tip might also reduce wire cracking and spalling through restraint.
gg) Excessive wire deformation might be improved by use of harder Ni wire.
hh) Removal of surface-film contamination should improve efficiency and variation.
ii) Use of wire slightly harder than plate might improve weldability.
jj) Plate and wires were cut into smaller pieces to avoid resonant vibrations.
kk) Wire was used in as-received condition without electropolishing.
ll) Use of electroetched wire should improve weldability.
mm) Grinding and electroetching of sheet and electroetching of wire are requisites for successful welding.
nn) Further study needed to improve weldability.
oo) Cold-worked plate and flattened, re-annealed wire might improve weldability.

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Table II

TEST RESULTS OF FINE-WIRE-TO-COUPON JUNCTURES

Weld Combination Materials			Joint	Tensile-Shear Strengths			Welder	
Coupon	Combination No.	Wire	Efficiency (percent)#	Base Wire* (lbs)(2)	Welded Wire* (lbs)(1)	Variation***	Used (watts)	Welding Comments
	1A	Copper	72	5.25 gm	3.8 gm**	0.158	20	b,h
	2A	Gold	52	2.7 gm	1.41 gm	1.17	20	b,h,k,l,m
	3A	Molybdenum	63	0.11 lb	0.069 lb	0	100	d,h,l,m
	4A	"A" Nickel	95	6.3 gm	6.01 gm	0.05	100	b,d,h
	5A	Rhenium						
Copper	6A	Silver	94	22.3 gm	20.96 gm	0.124	100	c
	7A	Mild Steel	86	0.26 lb	0.223 lb	0.493	100	c,f
	8A	St. Steel	96	0.333 lb	0.318 lb	0.047	100	h,d
	9A	Tantalum	96	0.48 lb	0.46 lb	0.141	100	e,j
	10A	Titanium	96	52.5 gm	50.4 gm	0.124	100	b,e,h
	11A	Tungsten	99	16.3 gm	16.15 gm	0.015	100	d,g,h,l,m
	12A	Copper	92	6.15 gm	5.7 gm	0.035	20	b,e,h
	13A	Gold	96	2.7 gm	2.6 gm	0.538	20	a,h,k
	14A	"A" Nickel	90	6.3 gm	5.69 gm	0.084	100	c,d,h
Gold	15A	Silver	100+	22.3 gm	22.4 gm	0.009	100	c
	16A	Mild Steel	81	0.26 lb	0.211 lb	0.450	100	d,h
	17A	St. Steel	88.5	0.333 lb	0.295 lb	0.118	100	d,n
	18A	Copper						
	19A	Molybdenum	15	0.11 lb	0.017 lb	1.17	100	g,h,l,m
	20A	"A" Nickel	93	6.3 gm	5.85 gm	0.196	100	b,f,h
	21A	Rhenium						
Molybdenum	22A	St. Steel	81	0.333 lb	0.27 lb	0.259	100	g,m
	23A	Tantalum	100+	0.48 lb	0.487 lb	0.010	100	h
	24A	Titanium	72	52.5 gm	37.7 gm	0.265	100	c,g,h,m
	25A	Tungsten	59	16.3 gm	9.68 gm	0.423	100	g,h,l,m
	26A	Copper	85	5.25 gm	4.5 gm	0.088	20	a,h
	27A	Gold	47	2.7 gm	1.3 gm	0.387	20	a,g,h,k,l,m
	28A	Molybdenum	59	0.11 lb	0.065 lb	0	100	d
	29A	"A" Nickel	98	6.3 gm	6.2 gm	0	100	b,e,h
	30A	Rhenium	100+	2.23 lb	2.46 lb	0.191	100	d,j,o
"A" Nickel	31A	Silver						
	32A	Mild Steel	98	0.26 lb	0.25 lb	0.078	100	b,e,h
	33A	St. Steel	96	0.333 lb	0.32 lb	0.093	100	e,j
	34A	Tantalum	87	0.48 lb	0.42 lb	0.214	100	c,e

	25A	Tungsten	59	16.3 gm	9.68 gm	0.423	100	g,h,l,m
"A" Nickel	26A	Copper	85	5.25 gm	4.5 gm	0.088	20	a,h
	27A	Gold	47	2.7 gm	1.3 gm	0.387	20	a,g,h,k,l,m
	28A	Molybdenum	59	0.11 lb	0.065 lb	0	100	d
	29A	"A" Nickel	98	6.3 gm	6.2 gm	0	100	b,e,h
	30A	Rhenium	100+	2.23 lb	2.46 lb	0.191	100	d,j,o
	31A	Silver						
	32A	Mild Steel	98	0.26 lb	0.25 lb	0.078	100	b,e,h
	33A	St. Steel	96	0.333 lb	0.32 lb	0.093	100	e,j
	34A	Tantalum	87	0.48 lb	0.42 lb	0.214	100	c,e
	35A	Titanium	81	52.5 gm	42.9 gm	0.263	100	b,h
	36A	Tungsten	94	16.3 gm	15.23 gm	0.164	100	e,g,h
Rhenium	37A	Copper						
	38A	Molybdenum	47	0.11 lb	0.052 lb	0.23	100	g,h,l,m
	39A	"A" Nickel	92	6.3 gm	5.78 gm	0.104	100	b,h,j
	40A	Rhenium						
	41A	St. Steel	93	0.333 lb	0.31 lb	0.064	100	a,h
	42A	Tantalum	87	0.48 lb	0.42 lb	0.047	100	c,g,j
	43A	Titanium	84	52.5 gm	43.8 gm	0.227	100	b,g,h,m
	44A	Tungsten						
Silver	45A	Copper	100+	5.25 gm	5.9 gm**	0.033	20	c,h
	46A	Gold	57	2.7 gm	1.55 gm	0.096	20	b,h,k,l,m
	47A	"A" Nickel	92	6.3 gm	5.81 gm	0.043	100	c,d,h
	48A	Silver	100	22.3 gm	22.3 gm	0.076	100	c
	49A	Mild Steel	72	0.26 lb	0.188 lb	0.585	100	d,h
	50A	St. Steel	86	0.333 lb	0.288 lb	0.364	100	d,h,m
Mild Steel	51A	Copper	75	5.25 gm	3.97 gm**	0.365	20	a,g,h
	52A	Gold						
	53A	"A" Nickel	92	6.3 gm	5.82 gm	0.01	100	b,h
	54A	Silver						
	55A	Mild Steel	83	0.26 lb	0.22 lb	0.348	100	b,g,h
	56A	St. Steel	70	0.333 lb	0.231 lb	0.952	100	g,j
Stainless Steel	57A	Copper						
	58A	Gold						
	59A	Molybdenum	57	0.11 lb	0.063 lb	0.079	100	b,e
	60A	"A" Nickel	94	6.3 gm	5.9 gm	0.203	100	b,h
	61A	Rhenium	83	2.23 lb	1.85 lb	0.864	100	b,e,j,o
	62A	Silver						
	63A	Mild Steel	92	0.26 lb	0.24 lb	0.083	100	a,g,h
	64A	St. Steel	79	0.333 lb	0.263 lb	0.114	100	g,j
	65A	Tantalum	100+	0.48 lb	0.51 lb	0.078	100	b,f,h
	66A	Titanium	90	52.5 gm	47.3 gm	0.063	100	g,h,m
	67A	Tungsten	84	16.3 gm	13.8 gm	0.252	100	d,g,h,l,m

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Table II (Concluded)

Weld Combination Materials			Joint Efficiency	Tensile-Shear Strengths			Welder	Welding
Coupon	Combination No.	Wire	(percent)#	Base Wire* (lbs)(2)	Welded Wire* (lbs)(1)	Variation***	Used (watts)	Comments
Tantalum	68A	Copper	85	5.25 gm	4.5 gm**	0.333	20	g,h
	69A	Molybdenum	62	0.11 lb	0.068 lb	0.058	100	g,h,l,m
	70A	"A" Nickel	92	6.3 gm	5.8 gm	0.155	100	a,h
	71A	Rhenium	64	2.23 lb	1.43 lb	0.391	100	j,o
	72A	St. Steel	88	0.333 lb	0.295 lb	0.338	100	g,j
	73A	Tantalum	89	0.48 lb	0.43 lb	0.302	100	g
	74A	Titanium	58	52.5 gm	30.66 lb	0.619	100	h
	75A	Tungsten****	94	13.13 gm	12.3 gm	0.024	100	g,h
Titanium	76A	Rhenium	100+	2.23 lb	2.55 lb	0.245	100	g,j,o
	77A	St. Steel	100+	0.333 lb	0.338 lb	0.044	100	c,h
	78A	Copper	60	5.25 gm	3.18 gm**	0.487	20	g,h
	79A	Molybdenum	64	0.11 lb	0.07 lb	0.214	100	e,b
	80A	"A" Nickel	95	6.3 gm	6 gm	0.133	100	b,e,g,h
	81A	Tantalum	100+	0.48 lb	0.493 lb	0.010	100	g
	82A	Titanium	98	52.5 gm	51.6 gm	0.096	100	g,h
	83A	Tungsten****	97	13.13 gm	12.8 gm	0	100	g,h
Tungsten	84A	Copper						
	85A	Molybdenum						
	86A	"A" Nickel	98	6.3 gm	6.18 gm	0.133	100	a,h
	87A	Rhenium						
	88A	St. Steel	76	0.333 lb	0.256 lb	0.058	100	g
	89A	Tantalum	100+	0.48 lb	0.481 lb	0.010	100	h
	90A	Titanium	44.5	52.5 gm	23.33 gm	1.36	100	c,h,m
	91A	Tungsten						

* Average of three individual shear strengths.
** Tensile-shear strength computed from average of two individual shear strengths.

*** Variation = $\frac{\text{highest shear-strength value - lowest shear-strength value}}{\text{average of individual shear strengths}}$

**** General Electric tungsten wire used.

= $\frac{\text{Col(1)}}{\text{Col(2)}} \times 100$ **Unrecorded efficiencies indicate minimal or inconsistent welds**

\+ After efficiency means higher average than unwelded wire.

SS is AISI stainless steel Type 304

	76A	Rhenium	100+	2.23 lb	2.55 lb	0.245	100	g,j,o
	77A	St. Steel	100+	0.333 lb	0.338 lb	0.044	100	c,h
	78A	Copper	60	5.25 gm	3.18 gm**	0.487	20	g,h
	79A	Molybdenum	64	0.11 lb	0.07 lb	0.214	100	e,b
Titanium	80A	"A" Nickel	95	6.3 gm	6 gm	0.133	100	b,e,g,h
	81A	Tantalum	100+	0.48 lb	0.493 lb	0.010	100	g
	82A	Titanium	98	52.5 gm	51.6 gm	0.096	100	g,h
	83A	Tungsten****	97	13.13 gm	12.8 gm	0	100	g,h
	84A	Copper						
	85A	Molybdenum						
	86A	"A" Nickel	98	6.3 gm	6.18 gm	0.133	100	a,h
	87A	Rhenium						
Tungsten	88A	St. Steel	76	0.333 lb	0.256 lb	0.058	100	g
	89A	Tantalum	100+	0.48 lb	0.481 lb	0.010	100	h
	90A	Titanium	44.5	52.5 gm	23.33 gm	1.36	100	c,h,m
	91A	Tungsten						

* Average of three individual shear strengths.
** Tensile-shear strength computed from average of two individual shear strengths.

*** Variation = $\frac{\text{highest shear-strength value - lowest shear-strength value}}{\text{average of individual shear strengths}}$

**** General Electric tungsten wire used.

= $\frac{\text{Col(1)}}{\text{Col(2)}} \times 100$ Unrecorded efficiencies indicate minimal or inconsistent welds

\+ After efficiency means higher average than unwelded wire.

SS is AISI stainless steel Type 304

Mild Steel is AISI 1010

WELDING COMMENTS

a) Wire flattened excessively.
b) Wire flattened moderately.
c) Wire flattened slightly.
d) Complete imbedding of wire into coupon.
e) Partial imbedding of wire into coupon.
f) Slight imbedding of wire into coupon.
g) Tip or tweezers were used to burnish the weld area on the coupon, thereby providing a smooth, flat surface.
h) Tip was used to make small reference mark on the coupon to insure exact wire location.
j) Occasionally, the wire broke outside of the joint area during the welding pulse.
k) A slight change of welding paramters proved critical for 0.003-inch gold wire.
l) For placement purposes, tweezers were used to grasp wire outside of pull-test length.
m) Portion of wire used for joining relatively free from dust and foreign matter.
n) Moderate deformation of coupon caused by "digging in" of tip.
o) Excessive hardening of wire during weld pulse.

2

Table III

RESULTS OF ULTRASONIC WELDING OF RHENIUM
TO ITSELF AND TO OTHER METALS IN AIR

Combination No.	Combination		Joint Efficiency	Tint 1)	
	Coupon	Wire		On the Coupon	On the Wire
5	Cu	Re	87%	Very slight brown or none	None
21	Mo	Re	No weld	Some yellow, dark purple with violet and blue, green, or only yellow some distance from the wire	None
30	Ni	Re	100%	Blue-black, or none	None
61	SS	Re	100%	Blue-black, brown, dark blue, green 2) or blue-black, dark blue, green, purple, dark yellow 3), 4)	None
71	Ta	Re	100%	Slight brown, occasional green	None
76	Ti	Re	100%	Slight dark brown, occasional dark blue or purple	None
87	W	Re	No weld	Blue-black, purple with some superimposed green, yellow or blue-black, purple, green, bluish	None
37	Re	Cu	No weld	None	None
38	Re	Mo	No weld	Occasional slight brown	Blue-black, some violet, some purple, some yellow 5)
39	Re	Ni	78%	None	None
40	Re	Re	74%	None or occasional slight mixed, black, green, yellowish, blueish	None
41	Re	SS	94%	None	Some yellowish, blueish, purple 5)
42	Re	Ta	100%	None	None
43	Re	Ti	No weld 6)	None	Very slight: blue-black, yellowish, violet
44	Re	W	No weld	None	Green, blue, some violet, brown, yellow

1) As appearing on the plate from the wire-outside or on the wire from the weld outside.
2) Made with 3-inch spherical radius sonotrode tip.
3) Made with grooved tip.
4) Identical welding machine settings.
5) Only on the sonotrode-work interface. These tints are probably due to heating stainless steel wire.
6) No weld possible. With the exception of one weld made with 0.001 tantalum foil interleaf when a strong weld was produced, neither tantalum or titanium foil produced any improvement. In contrast, rhenium wire welded very well to titanium plate.

Table IV

PHYSICAL AND MECHANICAL PROPERTIES MOLYBDENUM, TUNGSTEN AND RHENIUM
(21, 22, 23, 24, 25, 26)

Property	Molybdenum	Tungsten	Rhenium
		Physical Properties	
Melting Point, °C	2625	3410	3180
Boiling Point, °C	4800	5930	5900
Crystal Structure	BCC	BCC	HCP
Vapor Pressure at 2000°C, mm Hg	4×10^{-4}	1×10^{-7}	1×10^{-6}
Density g/cm^3	10.2	19.3	21.0
Electrical Resistivity at 20°C, ohm-cm x 10^{-6}	5.2	5.5	19.3
Electrical Conductivity, % IACS	31	32	9.3
Coefficient of Thermal Expansion, 20° to 500°C, x 10^{-6}	5.4	4.5	6.7
Modulus of Elasticity in Tension, psi x 10^6			
Room Temperature	48	59	66.7
Elevated Temperature	30 at about 860°C	About 52.5 at about 900°C	54 at about 880°C
		Mechanical Properties (Wires)	
Wire Diameter, inch	0.025	0.025	0.05
UTS, psi x 10^3			
Room Temperature			
Wrought	220	285	335
Recrystallization	70	80	170
Elev. Temp., Wrought,			
About 800°C	67	130	140
1200°C	38	70	80
1600°C		43	37
2000°C			15
Elongation, %			
Room Temperature			
Wrought	4	3	4-10 (est.)
Recrystallization	4	0	10
Elev. Temp., Wrought			
800°C	3.5	3.5	0.8
1200°C	5.5	6	0.8
1600°C			1.0
Hardness, DPH			
Annealed			270
30% Cold Reduced			Over 800

Table V

INTERSTITIAL CONTENT LIKELY TO BE MAINTAINED IN SOLID SOLUTIONS OF MOLYBDENUM, AND TUNGSTEN AND THEIR COMMERCIAL GRADES, IN PPM (15)

	Hydrogen		Carbon		Nitrogen		Oxygen	
Metal	Solubility	Actual	Solubility	Actual	Solubility	Actual	Solubility	Actual
Mo	0.1	1-3	0.1-1	5-500	1	1-56	1	1-60
W	N.d (1)	0-2	0.1	10-200	0.1	3-80	1	0-130

1) Not detectable.

Table VI

COMPARATIVE RESULTS OF ULTRASONICALLY WELDED TUNGSTEN TO ITSELF AND TO OTHER METALS IN AIR[1)]

Combination No.	Combination Coupon	Combination Wire	Joint Efficiency	Tint[2)] On the Coupon	Tint[2)] On the Wire
11	Cu	W	No weld	None	None
25	Mo	W	No weld	Light yellow	Light yellow or blue
36	Ni	W	85%	None	Blue, violet, yellow or green, violet, yellow
44	Re	W	No weld	None	Green, blue, brown, yellow, some violet
67	SS	W	83%	Brown[3)]	Black, green, blue, violet, yellow
75	Ta	W	72%	None	None or greenish-blue, blue, yellow
83	Ti	W	72%	None	Greenish-blue, blue, violet, yellow or violet, yellow
91	W[4)]	W[6)]	56%	None	Blue or greenish-blue, violet, yellow
	W[5)]	W[6)]	No weld	Blue, violet, yellow	Greenish-blue, violet, yellow
84	W	Cu	No weld	None	None
85	W	Mo	No weld	Green, violet, yellow or black-violet, yellow	Brown[7)]
86	W	Ni	100%	None	None
87	W	Re	No weld	Blue-black, purple with some superimposed green, yellow or blue-black, purple, green, blueish	None
88	W	SS	93%	None	Brown[3)]
89	W	Ta	97%	None	None
90	W	Ti	No weld	None	Slight brown[8)]

1) In some cases tungsten wire heated to a white heat during welding.
2) As appearing on the plate from the wire outside and on the wire from the weld outside.
3) Probably iron oxide.
4) Ground and electroetched.
5) Grooved.
6) Electroetched.
7) Probably molybdenum oxide.
8) Probably titanium oxide.

Table VII

COUPON BASE METAL DATA

Metal	Gage, inch	Hardness, DPH (1)	Notes
Copper	0.055	81.4	
Gold	0.060	46.8	
Molybdenum	0.058-0.065	269.4	Fansteel, as received
Molybdenum	0.060	247.6	Fansteel, electroetched
Nickel	0.060	129.2	"A Nickel", cold rolled
Rhenium	0.060-0.0625	396.0	
Silver	0.060	49.0	
Mild Steel	0.061-0.062	103.0	AlSl 1010, annealed
Stainless Steel	0.060	165.8	AlSl 304, annealed
Tantalum	0.060-0.063	104.8	
Titanium	0.067-0.070	141.0	
Tungsten	0.059-0.069	497.0	Fansteel, as received

(1) Checked on the surface of the plate.

Table VIII

BASE METAL DATA, FINE WIRE

Metal	Gage, inch	Tensile Strength Average*	Tensile Strength Units	Notes
Copper	0.0005	6.15	Gram	
Gold	0.0003	2.7	Gram	
Molybdenum	0.0008	0.11	Pounds	Fansteel, as received
Nickel	0.0005	6.3	Gram	
Rhenium	0.005	2.23	Pounds	
Silver	0.0015	22.3	Grams	
AlSl 1010 Steel	0.0015	0.26	Pounds	
AlSl 304 Stainless Steel	0.001	0.333	Pounds	AlSl 302
Tantalum	0.003	0.48	Pounds	
Titanium	0.001	52.5	Grams	
Tungsten	0.0003	16.3	Grams	
Tungsten	0.0003	13.13	Grams	General Electric, as received

* Average of four specimens.

Table IX

BASE METAL DATA, HEAVY WIRES

Metal	Gage, inch	Tensile Strength, pounds Average*	Hardness, DPH	Notes
Copper	0.064	114	58	
Gold	0.060	53	36	
Molybdenum	0.061	386	231.8 1)	Fansteel as received, steel relieved
Molybdenum	0.050	285	231.8 1)	Fansteel electroetched, stress relieved
Molybdenum	0.060	540	281.4 1)	Chatham Bright, as received
Molybdenum	0.050	316	281.4 1)	Chatham Bright, electro-polished
Molybdenum	0.060		243.8 1)	Chatham Dull, as received
Nickel	0.060	159	78.4	Annealed
Rhenium	0.061	360	326.6 2)	Annealed
Silver	0.060	76	45.8	Annealed
Mild Steel	0.0625	157	93.4	AlSl 1010, annealed
Stainless Steel	0.0625	268	164.4	AlSl 304, annealed
Stainless Steel	0.0625	819	536.0	AlSl 302, spring temper
Tantalum	0.062	151	110.2	Annealed
Titanium	0.063	256	231.8	Annealed
Tungsten	0.060	660	460.0 1)	As received
Tungsten	0.055-0.056	579	490.0 1)	Electropolished

* Average of 3 specimens

1) Center of the wire.
2) On the area without porosity.

Table X

ASSEMBLY SEQUENCE AND WELD JUNCTURES
FOR TYPE 6080WB ELECTRON TUBE

(All welds made with 600-watt welder)

Assembly Sequence Number	Key Number	Tip Number	Anvil Number	Description
1	1	T1	A1	Cathode tab to cathode sleeve
				Assemble 2 cathode sleeve assemblies to top spacer
2	2	T1	A1	Cathode tab to itself
				Assemble with in-process clamp, 2 grid assemblies, 2 anode-support Assemblies, spacer-cathode assembly, 8 lava spacers and bottom spacer
3	7	T2	A2	Anode eyelet to anode support
4	6	T3	A2	Grid eyelet to grid
5	5	T2	A2	Anode connector to anode support
6	11			Anode connector to anode support
7	3	T3	A2	Grid connector to grid
				Assemble one heater connector
8	4	T3	A2	Grid connector to grid
				Assemble other heater connector and 2 heaters - heater insulator assemblies
9	9	T1	A3	Heater to heater connector, heater sleeve
10	10	*	*	Grid radiator to grid
11	13a	T4	A4	Cathode connector to stem lead
12	14a	T4	A4	Cathode connector to stem lead
13	12b	T4	A4	Stem lead to grid connector
14	12c	T4	A4	Stem lead to anode connectors
15	12a	T4	A4	Stem lead to heater connectors
16	13b 14b	T4	A4	Snubber supports to cathode connector
17	15	**	**	Snubbers to snubber supports
				Assemble splash spacer - cathode connector assembly with splash spacer supports

(Concluded on next page)

Table X (Concluded)

ASSEMBLY SEQUENCE AND WELD JUNCTURES
FOR TYPE 6080WB ELECTRON TUBE

(All welds made with 600-watt welder)

Assembly Sequence Number	Key Number	Tip Number	Anvil Number	Description
18	18	T3	A5	Splash-spacer support to snubber support
19	16a	T3	A5	Top cathode connector to snubber support
20	16b	T1	A3	Cathode tabs to top cathode connector
21	17	***	***	Getters to snubber supports

* Will be resistance welded - inaccessible for ultrasonic welding

** Unsuccessful

*** Unsuccessful - crossed-wire weld

Table XI

WELD JUNCTURES FOR TYPE 5814WB ELECTRON TUBE

Key Number	Tip Number	Anvil Number	Welder (watt)	Description
1	T2	A1	100	Cathode tab to cathode
2A	T3	A3	600 **	Stem lead to plate
2B			Unsuccessful *	Stem lead to grid
2C	T1	A2	100	Stem lead to cathode tab
3A			Unsuccessful *	Heater connector to stem lead
3B	T2	A1	* 100 **	Heater connector to heater
4	T2	A1	100 **	Heater to stem lead
5	T4	A3	600	Getter to plate

* Crossed-wire weld

** Insufficient strength for use, although electrical conductivity was obtained

***Limited area available for production weld

Table XII

WELD JUNCTURES FOR TYPE 6205 ELECTRON TUBE

Key Number	Tip Number	Anvil Number	Welder (watt)	Description
1	T2	A2	100	Cathode tab to cathode
2A	T2	A2	100 *	Cathode tab to top shield
2B	T2	A2	100 *	Cathode tab to bottom shield
3	T3	A3	600	Stem shield to bottom shield
4A	T1	A2	100	#2 grid to grid connector
4B	T1	A2	100	#3 grid to grid connector
5	T1	A1	100 **	Heater connector to stem lead
6	T3	A4	600	Bottom shield to stem lead
7	T2	A2	100 ***	Heater to heater connector
8	T4	A4	600	#1 grid to stem lead
9	T4	A3	600	Plate to stem lead
10	T3	A3	600****	Getter to top shield
11	T1	A2	100	Grid connector to stem lead

* Material combinations and geometrical configurations are identical

** 600 w welder may be required to produce stronger junction

*** Insufficient strength for use, although electrical conductivity was obtained

**** Getter construction precludes production use because of damage to oxide content

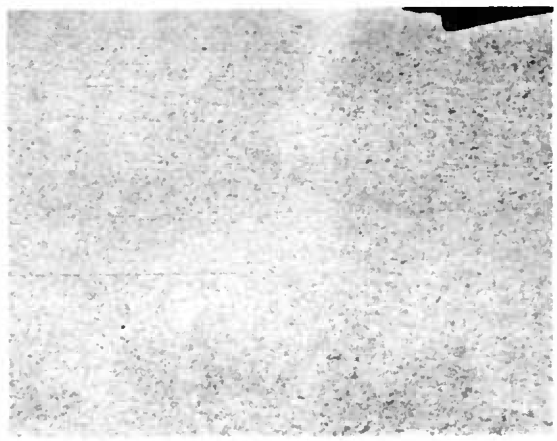
APPENDIX A

METALLOGRAPHY

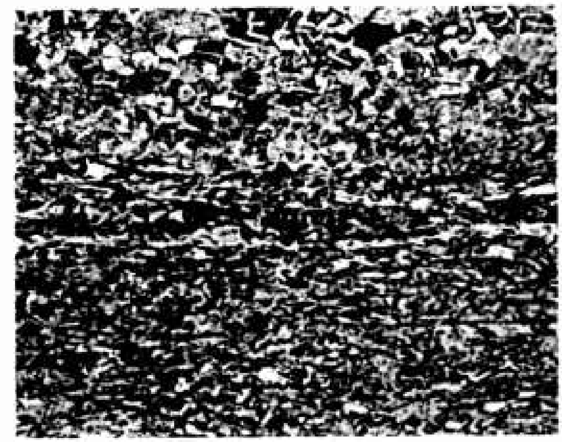
Etchant: Ammonium hydroxide + hydrogen peroxide

Combination: Number 1 — Copper (wire) 0.064 gage to Copper (coupon) 0.055

Longitudinal

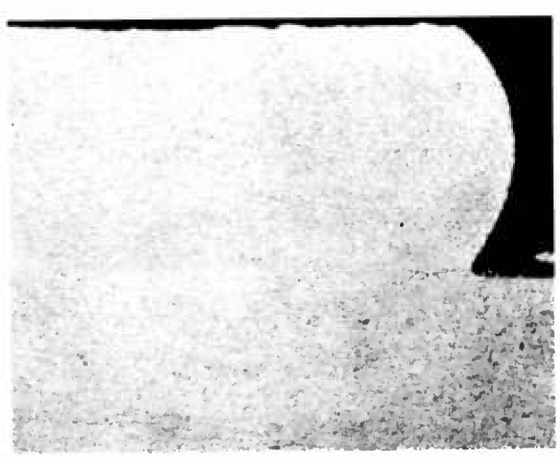


Magnification: 36X



Magnification: 250X

Transverse



Magnification: 36X

Magnification: 250X

Comments: Very good bonding characteristics. Note extrusion of material from edge of weld and recrystallized interface region.

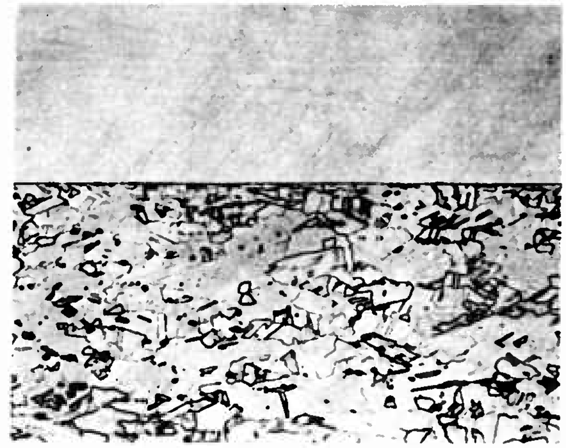
METALLOGRAPHY

Etchant: Ammonium hydroxide
+ hydrogen peroxide

Combination: Gold (wire) 0.060 to Copper (coupon) 0.055 gage
Number 2

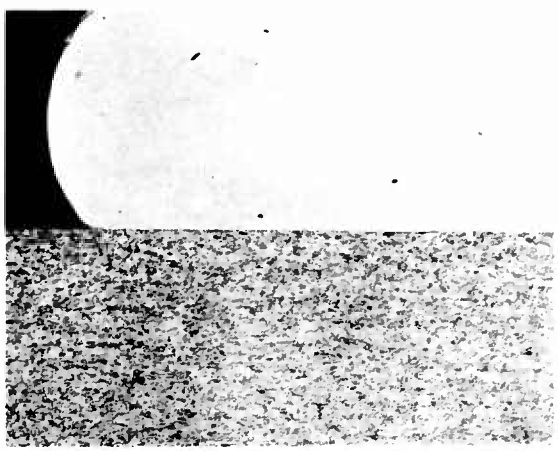
Longitudinal

Magnification: 40X



Magnification: 250X

Transverse



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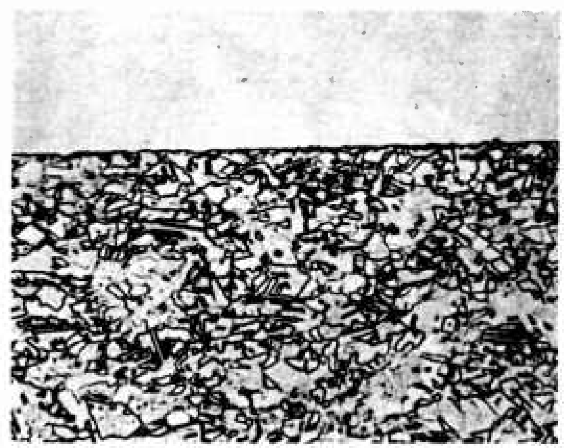


Magnification: 250X

Comments: Intimate contact established by yielding of the gold wire results in bonding without mutual interpenetration of the faying surfaces.

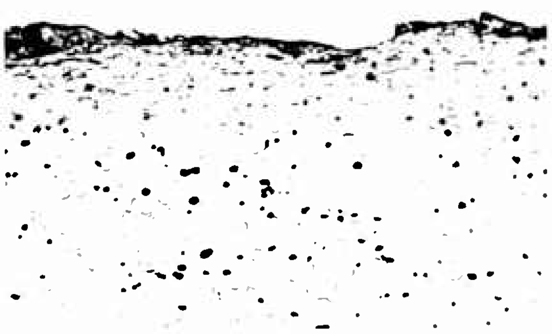
METALLOGRAPHY

Etchant: $NH_4OH + H_2O_2$
(Nickel unetched)

Combination: Nickel to Copper
Number 4 (Wire) (Coupon)
0.060 gage 0.055

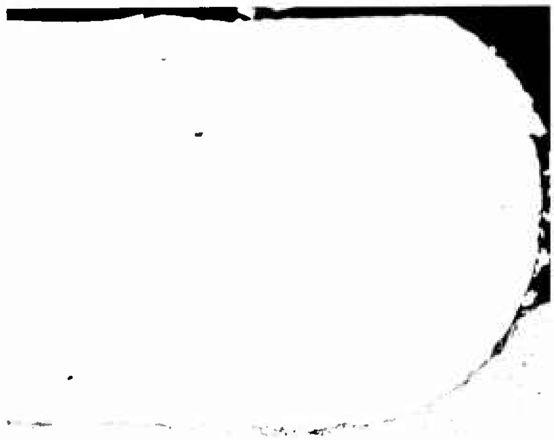
Longitudinal

Magnification: 52X

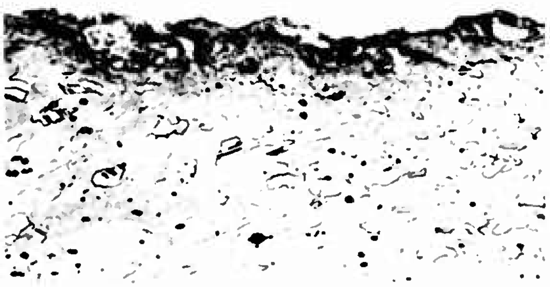


Magnification: 250X

Transverse



Magnification: 52X
Reduced to 3/4 Size



Magnification: 250X

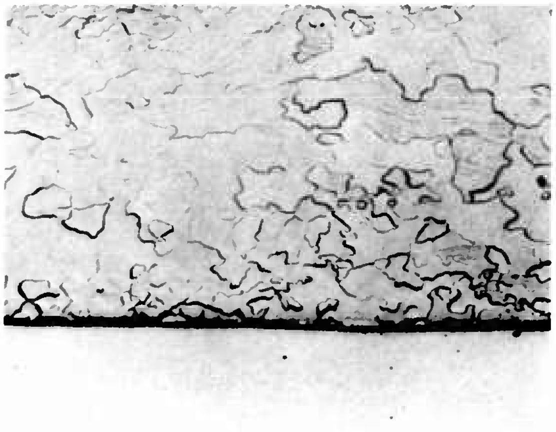
Comments: This joint displays excellent bonding characteristics. External deformation is small. The weld interface contains good interpenetration along with associated turbulent flow, uniformity of bond quality, and absence of imperfection such as voids or unbonded areas. The weld edge shows minimum crevasse formation.

METALLOGRAPHY

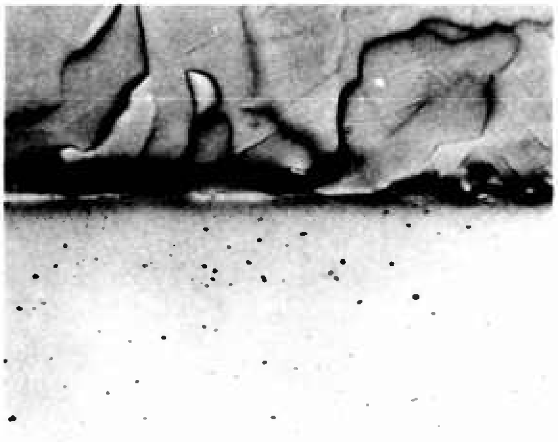
Etchant: Alkaline ferricyanide solution

Combination: Number 5 — Rhenium (wire) 0.061 to Copper (coupon) gage 0.055

Longitudinal

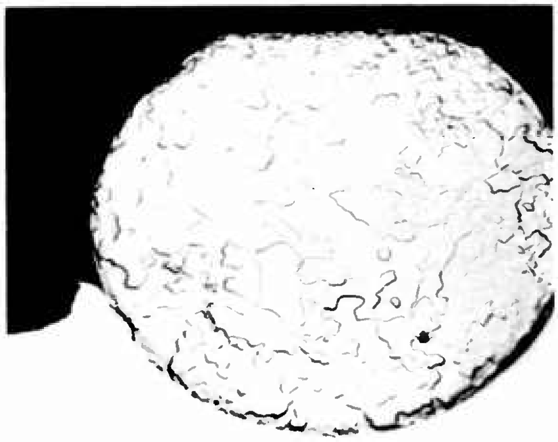


Magnification: 38X

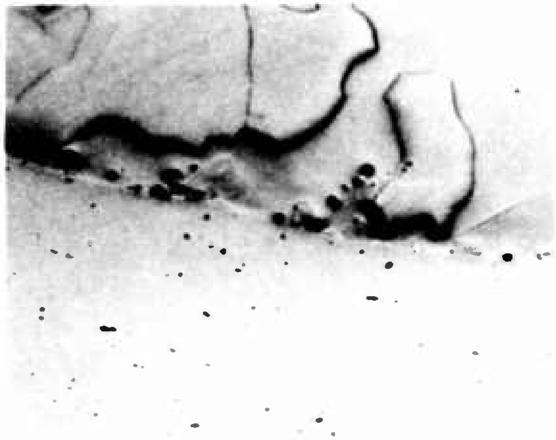


Magnification: 250X

Transverse



Magnification: 38X



Magnification: 250X

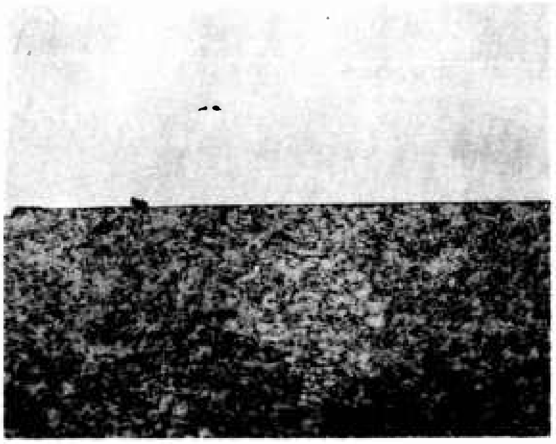
Comments: The interface appears dark in the longitudinal section from polishing relief. The interface of both sections indicates that satisfactory bonding has been achieved.

METALLOGRAPHY

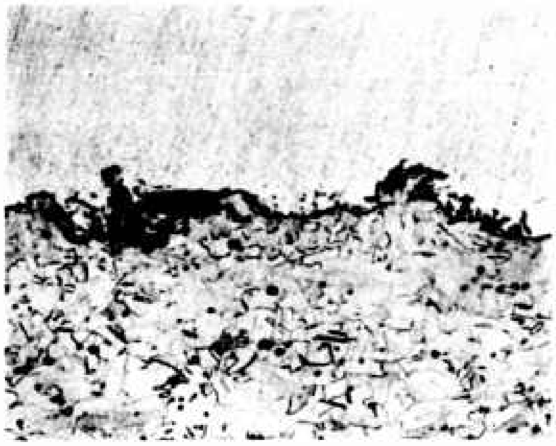
Etchant: $NH_4OH + H_2O_2$
(Silver unetched)

Combination: Silver (Wire) 0.060 to Copper (Coupon) gage 0.055
Number 6

Longitudinal

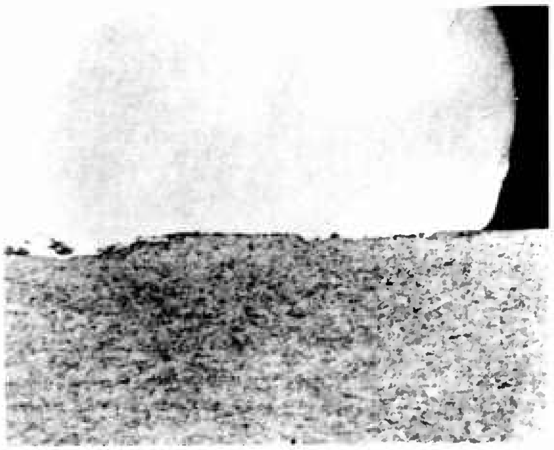


Magnification: 52X



Magnification: 250X

Transverse



Magnification: 63X
Reduced to 3/4 Size

Magnification: 250X

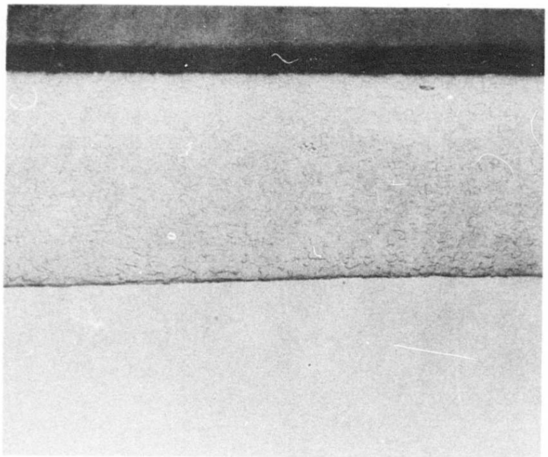
Comments: The joint shows a high degree of interpenetration and interfacial flow. Bond quality is uneven, but satisfactory bonding was achieved along the center of the wire-sheet contact surface. The longitudinal section illustrates only a small portion of the weld zone.

METALLOGRAPHY

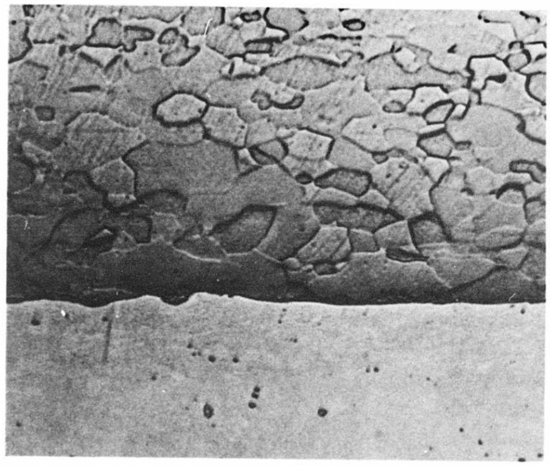
Etchant:

Combination: Number 9 — Tantalum (wire) to Copper (coupon)
0.062 gage 0.055

Longitudinal

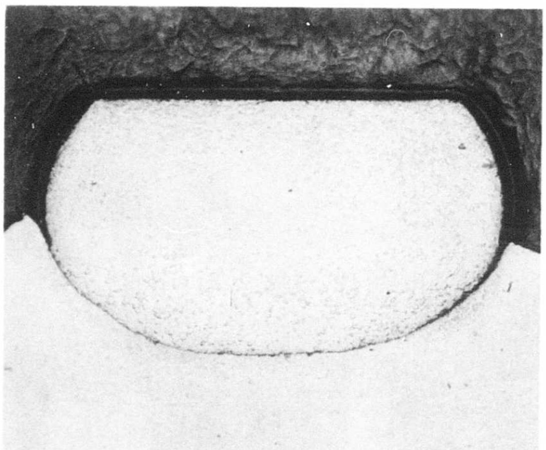


Magnification: 32X

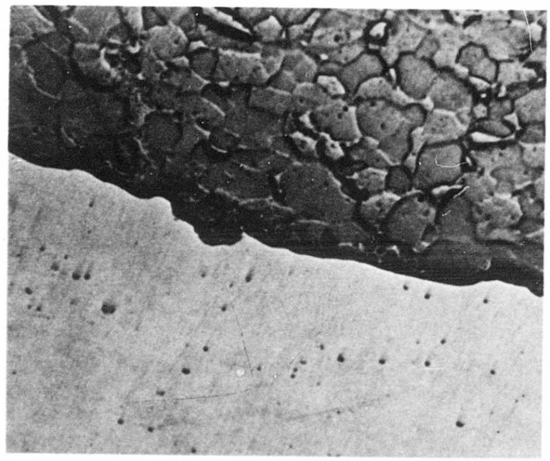


Magnification: 250X

Transverse



Magnification: 32X



Magnification: 250X

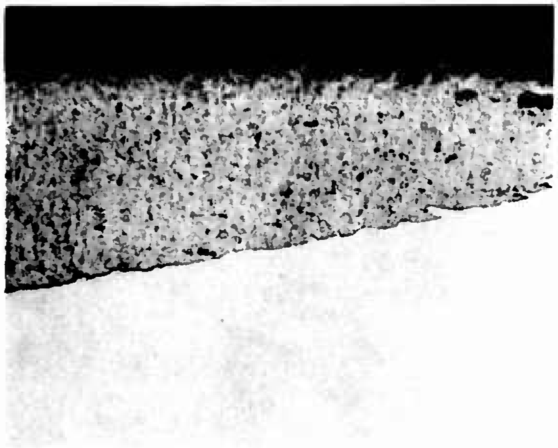
Comments: Interface detail cannot be resolved but weld appears satisfactory - no voids or separation were observed.

METALLOGRAPHY

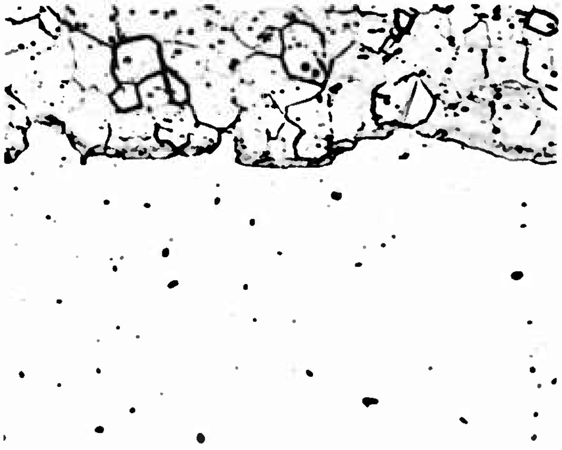
Etchant: HF + HNO_3 + H_2O

Combination: Titanium to Copper
Number 10 (wire) (coupon)
0.063 gage 0.055

Longitudinal



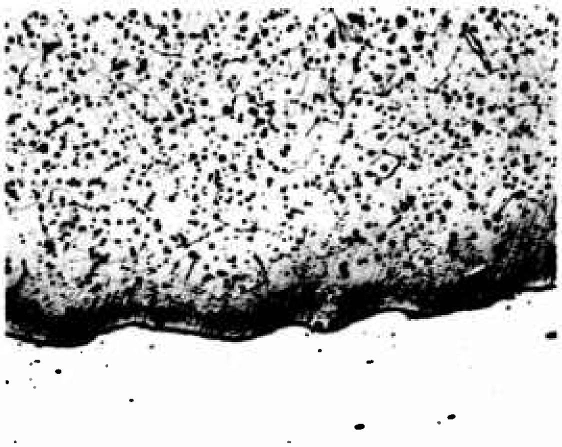
Magnification: 40X



Magnification: 250X

Transverse

Magnification: 66X



Magnification: 250X

Comments: This series of photographs illustrates how the character of the bond line is altered by etch attack. Both samples were contained in the same specimen mount. The transverse orientation was preferentially etched at the interface and the titanium wire was pitted. The longitudinal section shows the interface preserved. Note porosity in titanium wire. This weld shows good bonding characteristics.

METALLOGRAPHY

Etchant: KCN + $NH_4S_2O_8$ + H_2O

Combination: Number 12 — Copper to Gold; (wire) 0.064 gage (coupon) 0.060

Longitudinal

Magnification: 40X

Magnification: 250X

Transverse

Magnification: 40X

Magnification: 250X

Comments: Excellent bond characteristics - interpenetration and plastic deformation with surface film dispersion - are exhibited in this weld.

METALLOGRAPHY

Etchant: KCN + $NH_4S_2O_8$ + H_2O

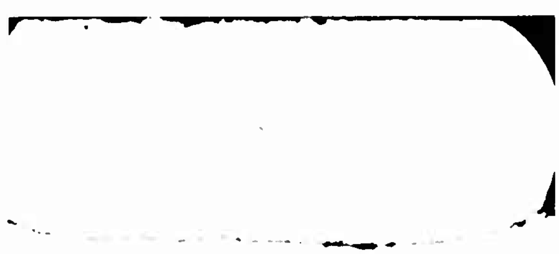
Combination: Gold to Gold
Number 13 (wire) (coupon)
0.060 gage 0.060

Longitudinal

Magnification: 36X

Magnification: 250X

Transverse



Magnification: 36X

Magnification: 250X

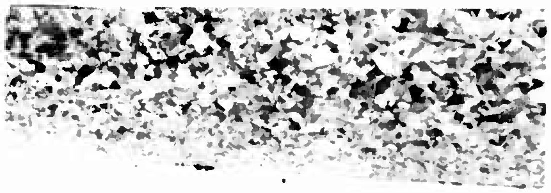
Comments: Bond quality is generally unsatisfactory. Only small areas of structural continuity exist; non-bonded areas occupy most of the interface.

METALLOGRAPHY

Etchant: KCN + $NH_4S_2O_8$ + H_2O
(Gold unetched)

Combination: Nickel to Gold
Number 14 (Wire) (Coupon)
0.060 gage 0.060

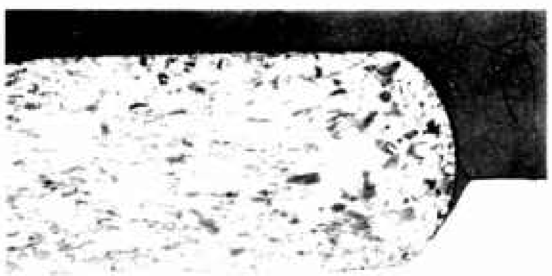
Longitudinal



Magnification: 36X

Magnification: 250X

Transverse



Magnification: 36X

Magnification: 250X

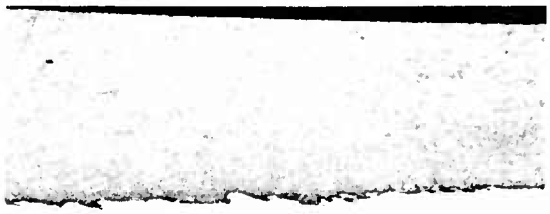
Comments: Several small voids are present at the interface, but in general, joint integrity is good. The lack of appreciable interpenetration is to be expected with metals of different hardness. The edges of the flattened wire are not bonded.

METALLOGRAPHY

Etchant: KCN + $NH_4S_2O_8$ + H_2O
(Gold Unetched)

Combination: Number 15 — Silver to Gold
(wire) (coupon)
0.060 gage 0.060

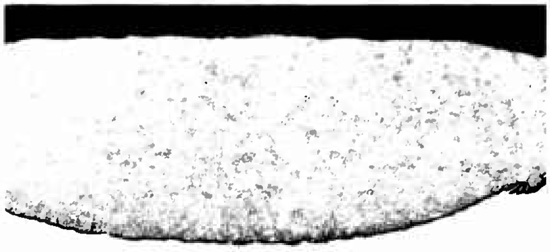
Longitudinal



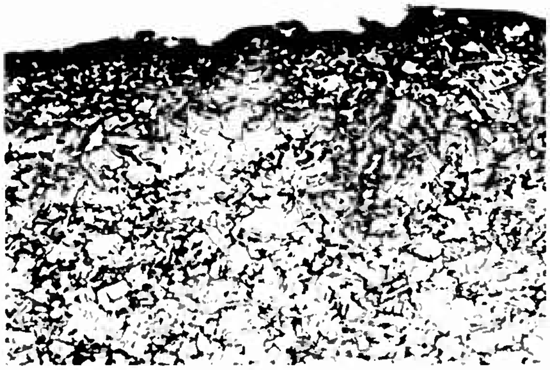
Magnification: 36X

Magnification: 250X

Transverse



Magnification: 36X



Magnification: 250X

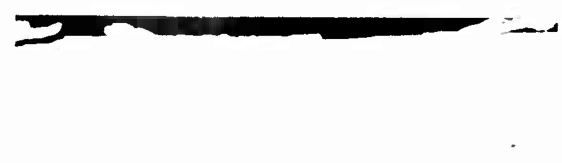
Comments: This couple, which employs metals of similar hardness range, exhibits excellent bonding. Complete edge-to-edge bonding has been achieved and the mutual plastic turbulence between the faying surfaces has produced a high degree of interpenetration and a void-free junction.

METALLOGRAPHY

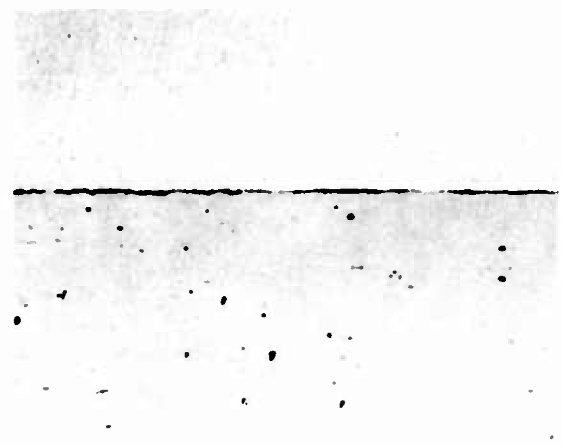
Etchant: Unetched

Combination: AISI 1010 Steel (wire) to Gold (coupon)
Number 16
0.063 gage 0.060

Longitudinal

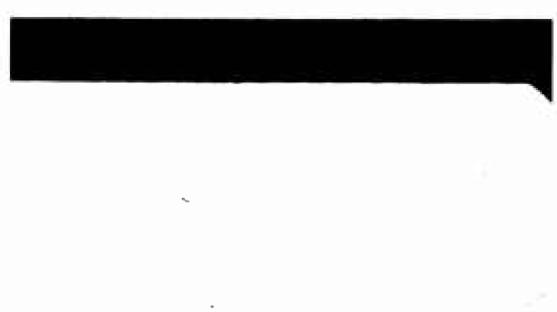


Magnification: 38X



Magnification: 250X

Transverse



Magnification: 38X

Magnification: 250X

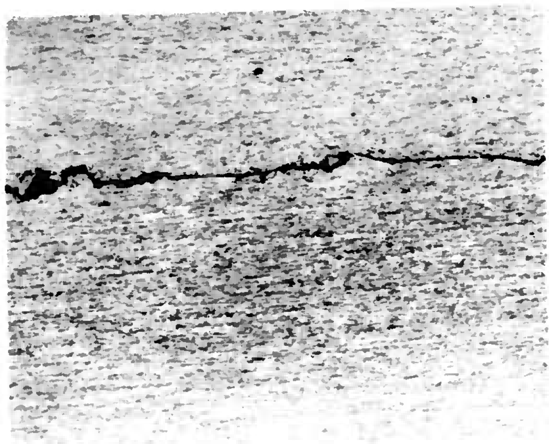
Comments: Although joint efficiency of 97% was achieved, bond quality is generally unsatisfactory in this sample. The extent of the unbonded areas cannot be reconciled with the high strength exhibited by similar samples.

METALLOGRAPHY

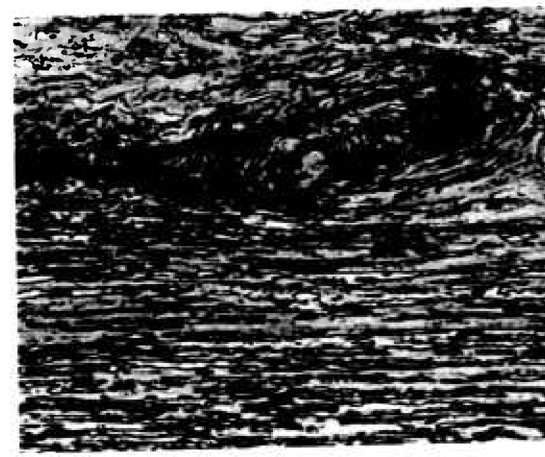
Etchant: Alkaline ferricyanide solution

Combination: Number 19 — Molybdenum (wire) 0.050 gage to Molybdenum (coupon) 0.060

Longitudinal

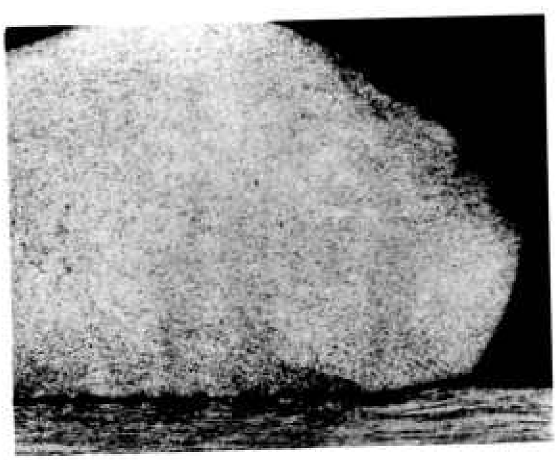


Magnification: 59X



Magnification: 250X

Transverse



Magnification: 59X

Magnification: 250X

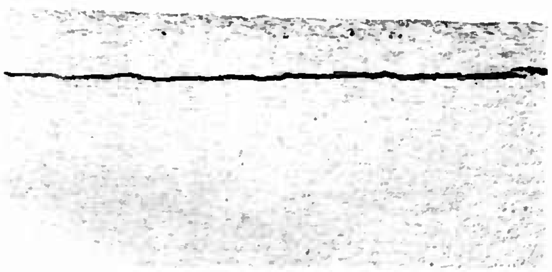
Comments: Almost complete weld separation was observed.

METALLOGRAPHY

Etchant: Alkaline ferricyanide solution

Combination: Number 20 — "A" Nickel (wire) 0.060 gage to Molybdenum (coupon) 0.060

Longitudinal

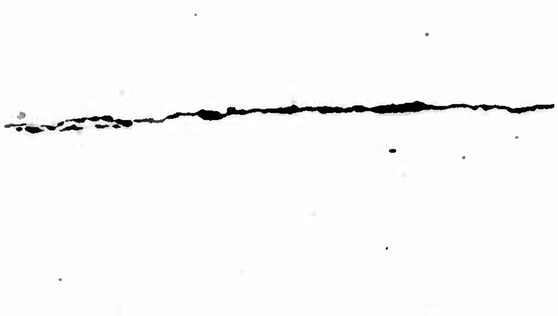


Magnification: 40X

Magnification: 250X

Transverse

Magnification: 40X



Magnification: 250X

Comments: Strength measurements indicate good weldability, shown by the longitudinal section. The transverse section was apparently taken in an area where incomplete bonding and weld separation had occurred. Note the network of cracks in the molybdenum below the interface.

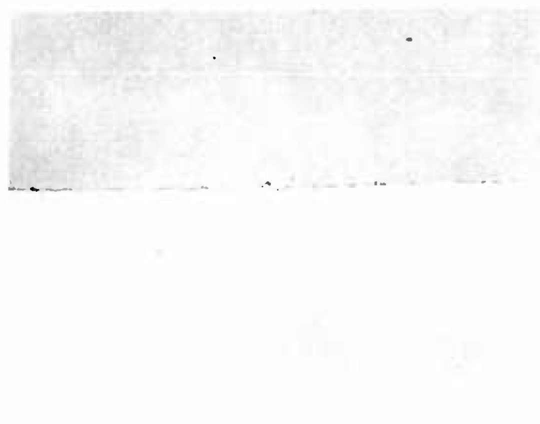
METALLOGRAPHY

Etchant: Alkaline ferricyanide solution

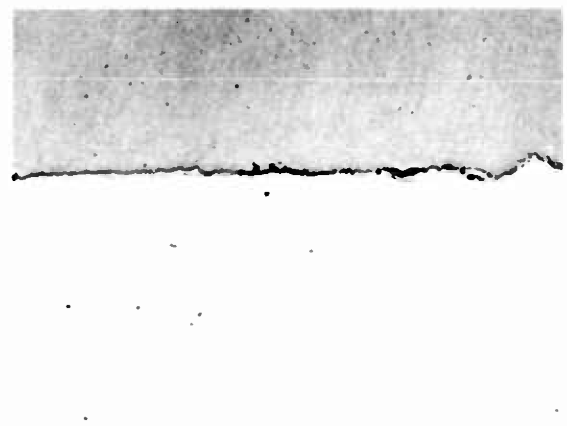
Combination: Number 23

Tantalum (wire) 0.062 to Molybdenum (coupon) gage 0.060

Longitudinal



Magnification: 45X



Magnification: 250X

Transverse

Magnification: 45X

Magnification: 250X

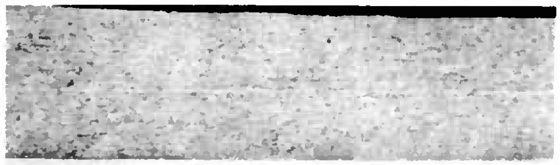
Comments: Bond quality is unsatisfactory. Profuse non-bonds decorate the interface. The number and strength of the local junctions is sufficient to produce good joint efficiency.

METALLOGRAPHY

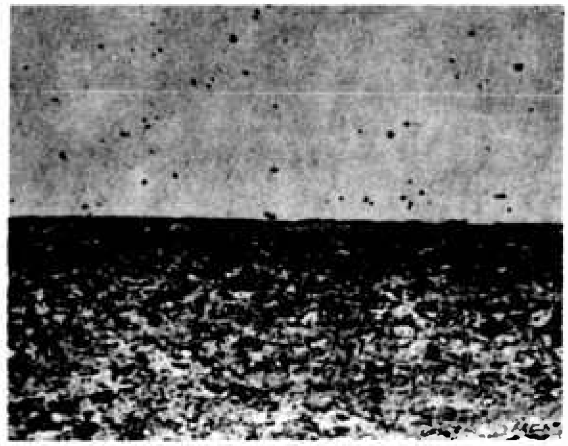
Etchant:

Combination: Number 26 — Copper to "A" Nickel
(wire) (coupon)
0.064 gage 0.060

Longitudinal

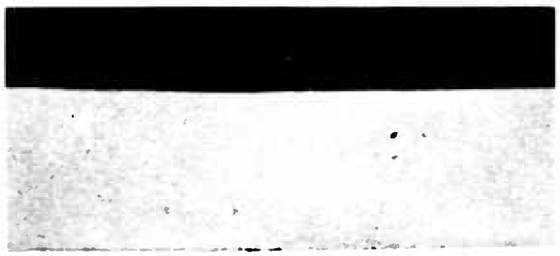


Magnification: 36X

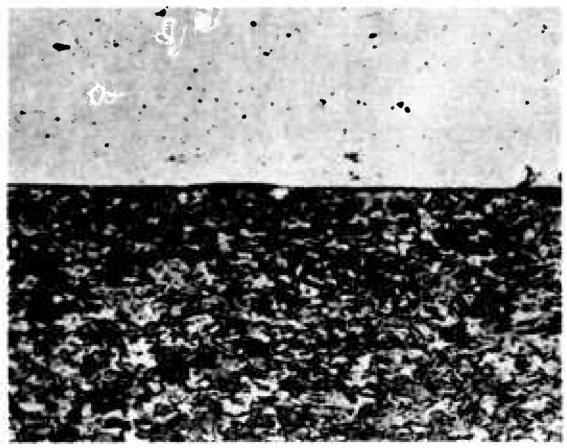


Magnification: 250X

Transverse



Magnification: 36X



Magnification: 250X

Comments: Interface voids in transverse section. Adhesion is adequate to produce high joint efficiencies.

METALLOGRAPHY

Etchant: Alkaline ferricyanide solution

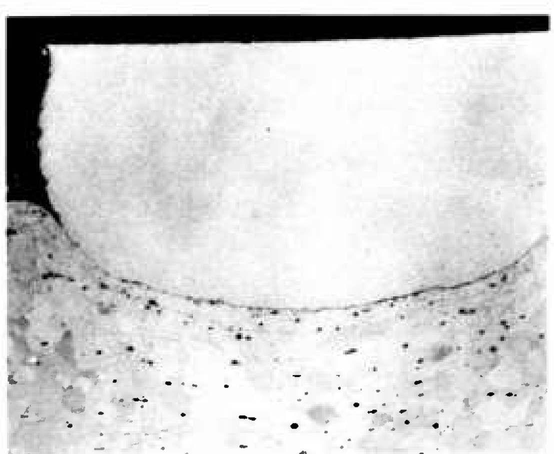
Combination: Molybdenum to "A" Nickel
Number 28 (wire) (coupon)
0.061 gage 0.060

Longitudinal

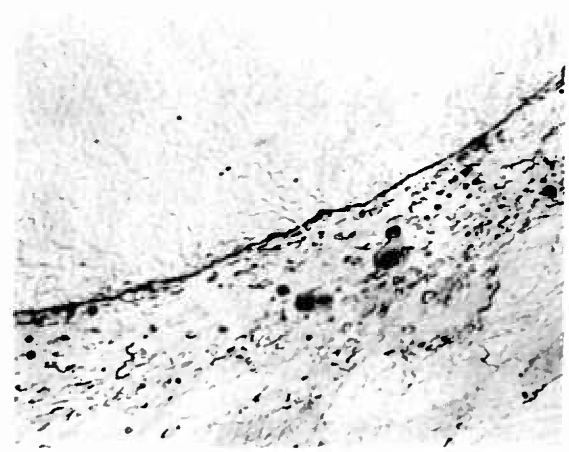
Magnification: 36X

Magnification: 250X

Transverse



Magnification: 36X



Magnification: 250X

Comments: Bonding is accompanied by recrystallization of the nickel along the interface. No voids or separations were observed.

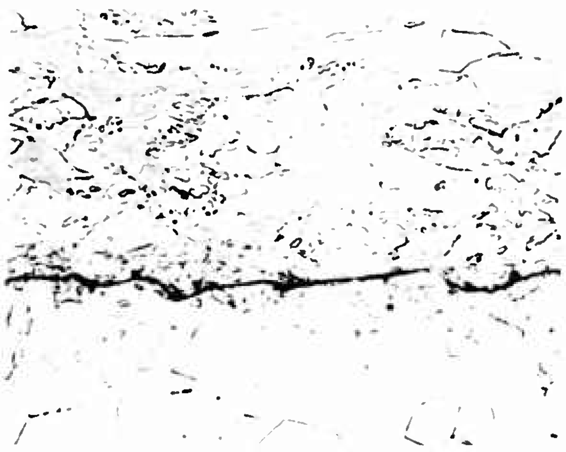
METALLOGRAPHY

Etchant: KCN + $NH_4S_2O_8$ + H_2O

Combination: "A" Nickel to "A" Nickel
Number 29 (wire) (coupon)
0.060 gage 0.060

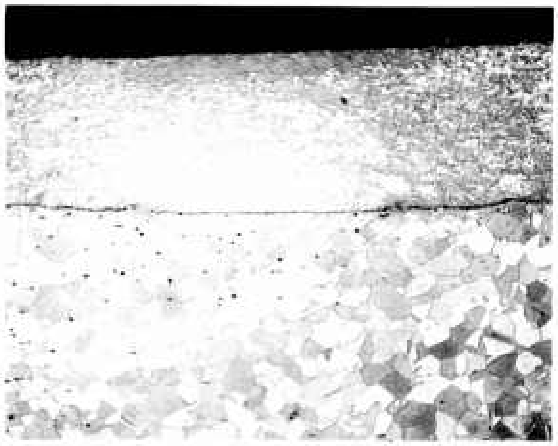
Longitudinal

Magnification: 36X



Magnification: 250X

Transverse



Magnification: 36X

Magnification: 250X

Comments: Despite severe deformation of the wire, uniform bonding was not achieved. The central area of the joint is unbonded. Bond quality and uniformity may be improved by modified tooling or surface preparation.

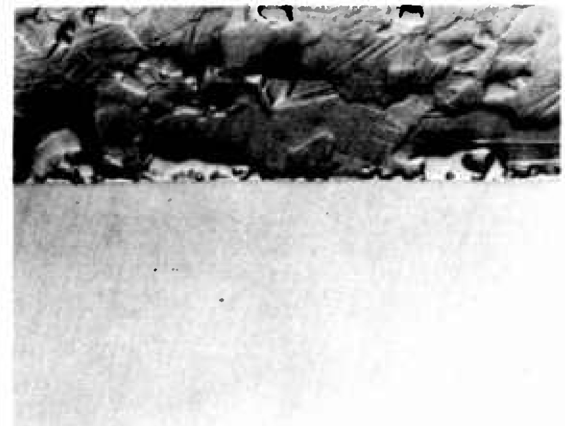
METALLOGRAPHY

Etchant: Alkaline ferricyanide solution

Combination: Rhenium to "A" Nickel
Number 30 (wire) (coupon)
0.060 gage 0.060

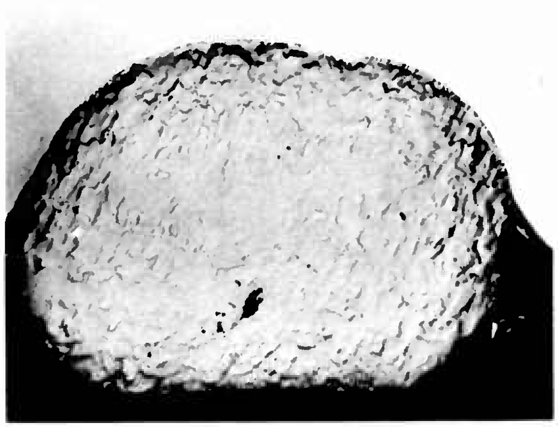
Longitudinal

Magnification: 38X

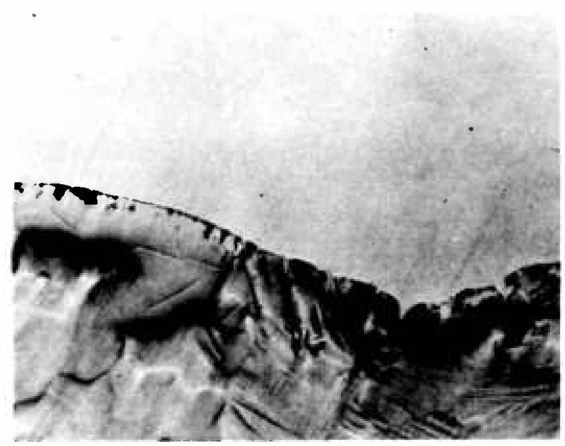


Magnification: 250X

Transverse



Magnification: 38X



Magnification: 250X

Comments: Dark areas in rhenium wire are voids. Bonding appears satisfactory in longitudinal section. Microvoids decorate the rhenium interface in the transverse section. Note partial extrusion of the nickel into the void areas.

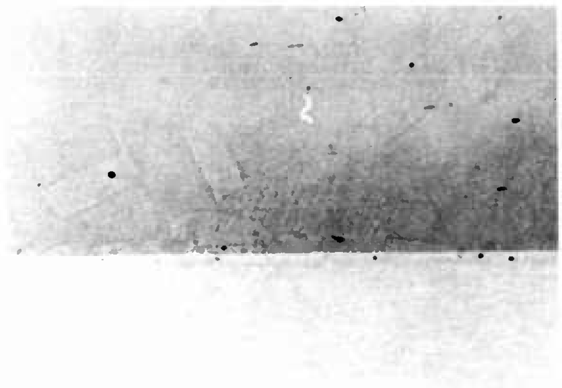
METALLOGRAPHY

Etchant:

Combination: Number 31 — Silver to "A" Nickel
(wire) (coupon)
0.060 gage 0.060

Longitudinal

Magnification: 36X



Magnification: 250X

Transverse

Not Sectioned in Transverse Plane

Magnification:

Magnification:

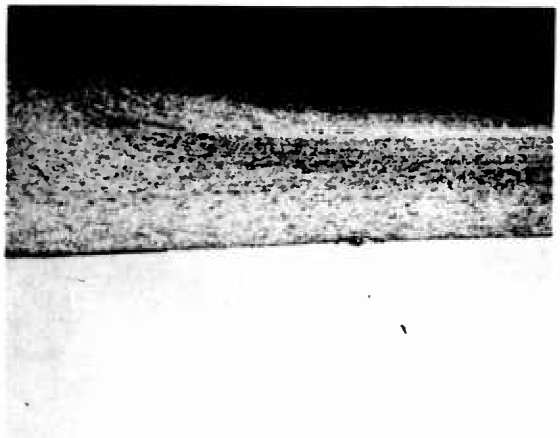
Comments: Deformation of the silver wire results in intimate surface contact.

METALLOGRAPHY

Etchant: 1% Nital (Nickel Unetched)

Combination Number 32: AISI 1010 Steel (wire) 0.0625 gage to "A" Nickel (coupon) 0.060

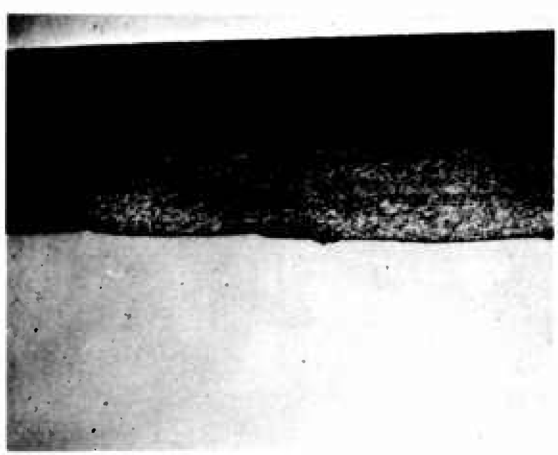
Longitudinal



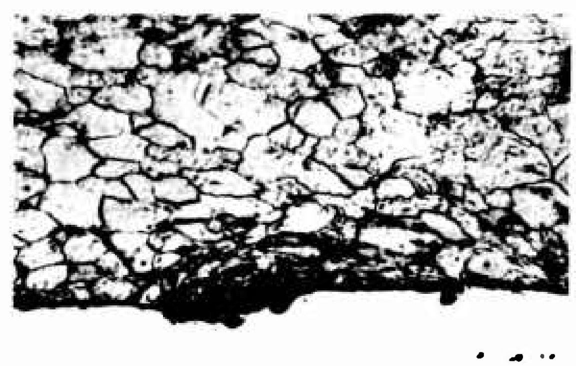
Magnification: 36X

Magnification: 250X

Transverse



Magnification: 36X



Magnification: 250X

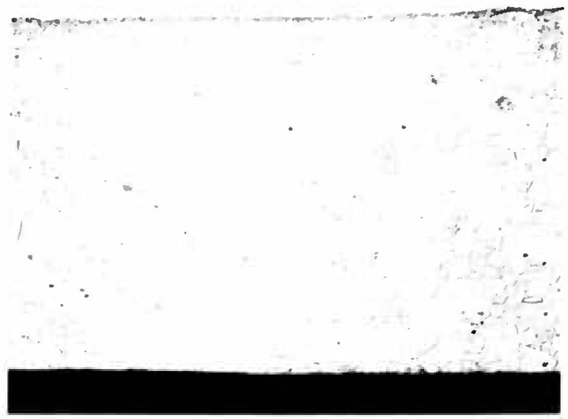
Comments: The irregular interface is produced by the deformation of the wire during welding. Inferior edge bonding has resulted. The heat pattern in the wire is revealed by the etch.

METALLOGRAPHY

Etchant: $KCN + NH_4S_2O_8 + H_2O$
(Stainless Steel Unetched)

Combination: Number 33
AISI 304 Stainless Steel (Wire) 0.0625 to Nickel (Coupon) gage 0.060

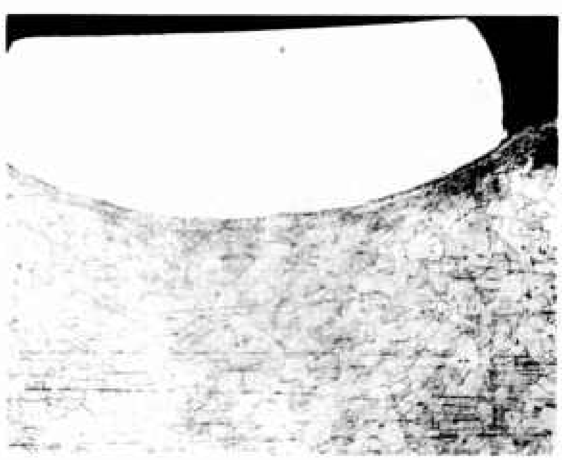
Longitudinal



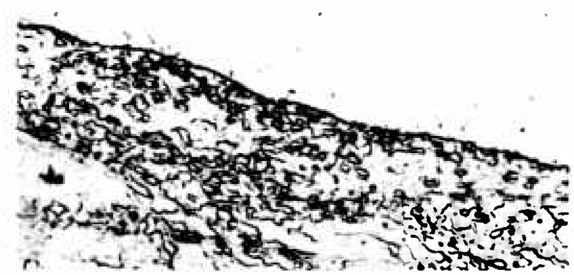
Magnification: 36X

Magnification: 250X

Transverse



Magnification: 36X
Reduced to 3/4 Size



Magnification: 250X

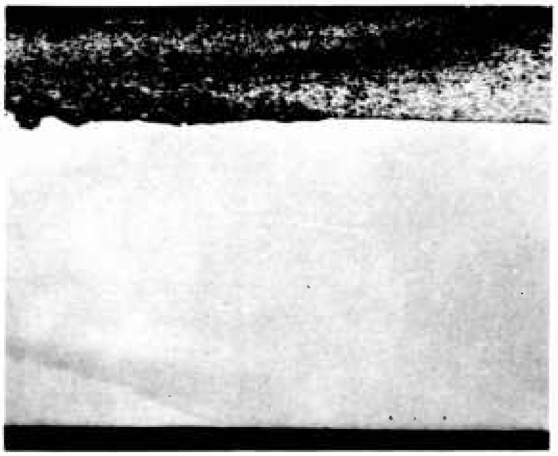
Comments: Satisfactory weld characteristics are evident. Mutual interpenetration of the faying surfaces and absence of voids or non-bond areas indicate the integrity of the joint. Note the flow and expulsion of the nickel sheet and recrystallization structure adjacent to the weld interface.

METALLOGRAPHY

Etchant: HF + HNO_3 + Lactic Acid

Combination: Number 34 — Tantalum (Wire) to Nickel (Coupon)
0.062 gage 0.060

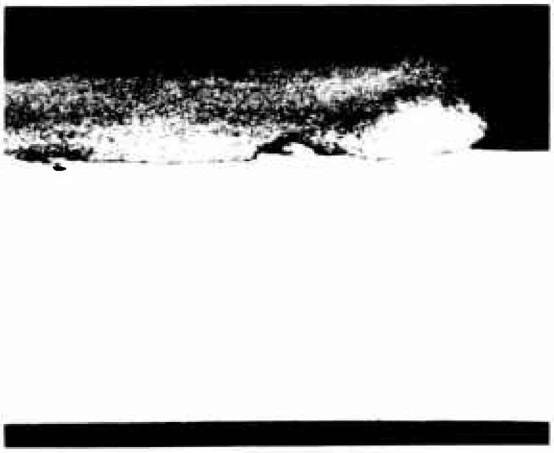
Longitudinal



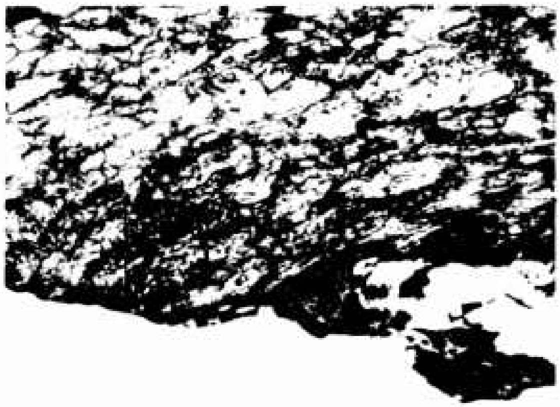
Magnification: 36X

Magnification: 250X

Transverse



Magnification: 36X
Reduced to 3/4 Size



Magnification: 250X

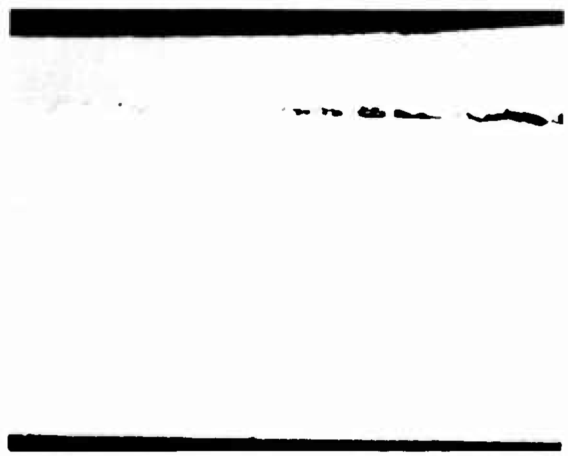
Comments: Uniform bonding throughout the entire contact area has not occurred, but excellent local bond areas are present. The darkly-etched regions of the wire delineate the heat pattern developed during welding.

METALLOGRAPHY

Etchant: Unetched

Combination: Titanium to "A" Nickel
Number 35 (wire) (coupon)
0.063 gage 0.060

Longitudinal



Magnification: 30X

Magnification: 250X

Transverse

Magnification: 30X

Magnification: 250X

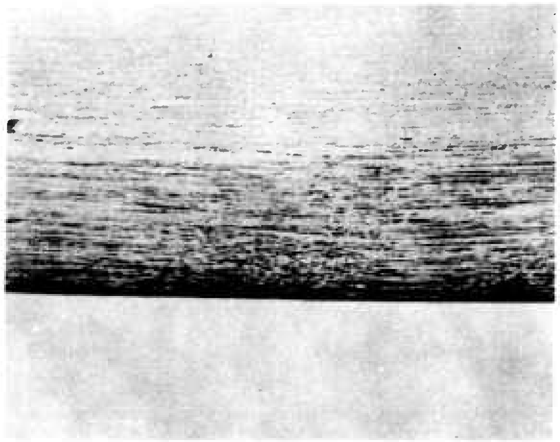
Comments: Bonding occurs only in the central area of the faying surfaces where the curvature of the wire was maintained. Good interpenetration with a few void regions characterize the bond. Weld quality was judged satisfactory, but improved tooling such as a grooved tip (see above) might reduce the degree of non-bonding at the edge of the wire.

METALLOGRAPHY

Etchant: $KOH + K_3Fe(CN)_6 + H_2O$
(Nickel Unetched)

Combination:	Tungsten to	Nickel
Number 36	(Wire)	(Coupon)
	0.055	gage 0.061

Longitudinal

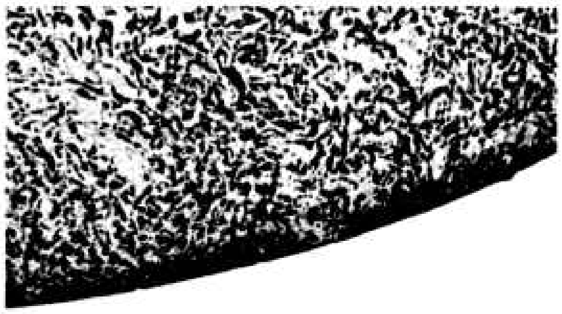


Magnification: 48.5X

Magnification: 250X

Transverse

Magnification: 48.5X



Magnification: 250X

Comments: Very good integrity of the mating surfaces is demonstrated. However, evaluation of bond quality must be deferred because of polishing relief at the interface. Note cracking and spalling of tungsten wire.

METALLOGRAPHY

Etchant: Alkaline ferricyanide solution

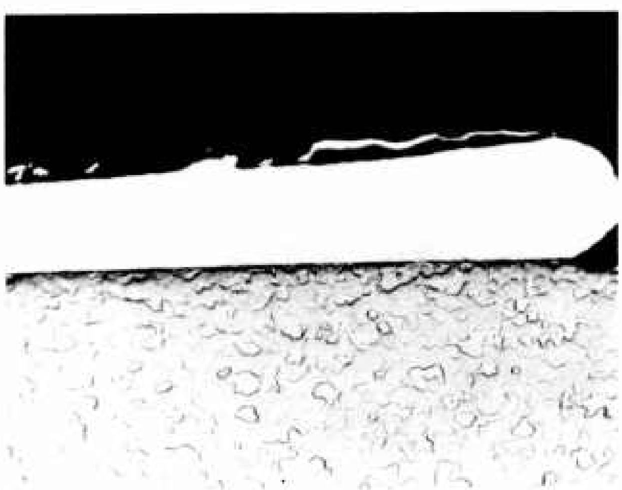
Combination: "A" Nickel to Rhenium
Number 39 (wire) (coupon)
0.060 gage 0.060

Longitudinal

Magnification: 38X

Magnification: 250X

Transverse



Magnification: 38X

Magnification: 250X

Comments: Microvoids at the interface are evident; the bond appears to exist by physical adhesion of the deformed nickel and rhenium surfaces. The dark streaks at the interface are elongated pits produced by etch-polishing.

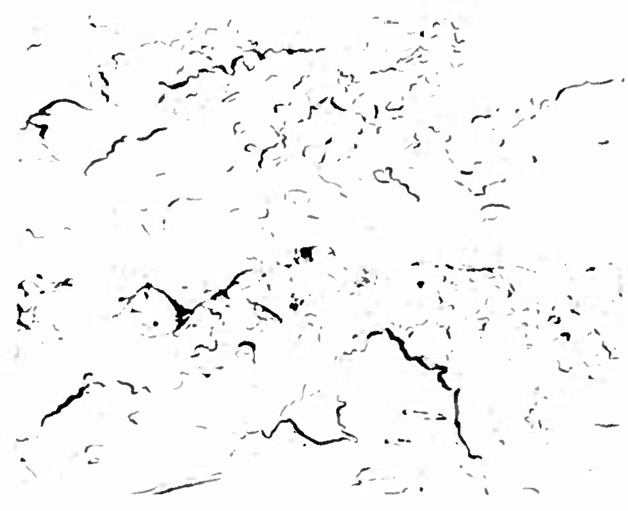
METALLOGRAPHY

Etchant: Alkaline ferricyanide solution

Combination: Rhenium to Rhenium
Number 40 (wire) (coupon)
0.060 gage 0.060

Longitudinal

Magnification: 36X



Magnification: 250X

Transverse

Magnification: 36X

Magnification: 250X

Comments: Note extreme porosity in the rhenium wire. Very good bonding was achieved along the edges of the contact surface; the central area is less well bonded. Areas of grain refinement appear to result from partial recrystallization during welding.

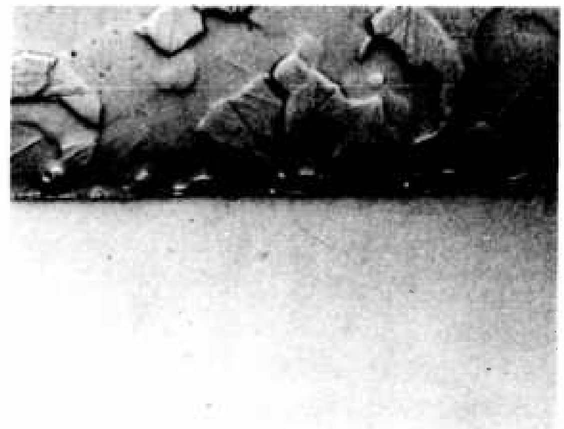
METALLOGRAPHY

Etchant: Alkaline ferricyanide solution

Combination: AISI 304 St. Steel to Rhenium
Number 41 (wire) (coupon)
0.060 gage 0.0625

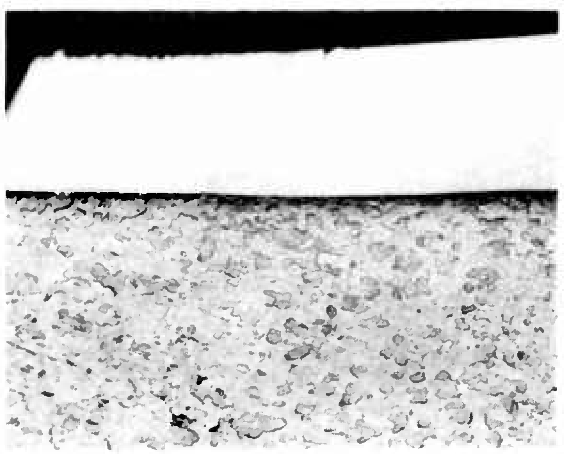
Longitudinal

Magnification: 32X

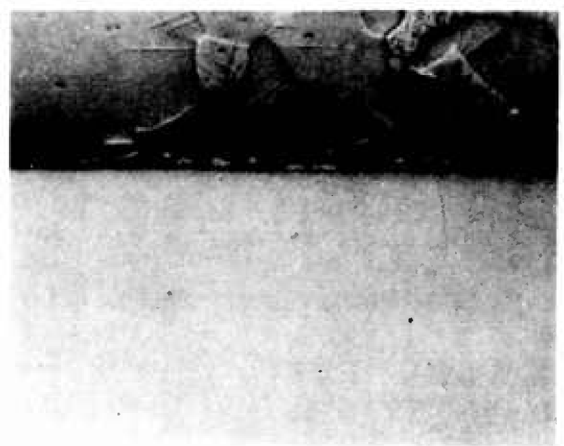


Magnification: 250X

Transverse



Magnification: 32X



Magnification: 250X

Comments: Deformation of the stainless steel wire produced intimate surface contact. There is evidence of an alloy layer or barrier film along the interface. Good bonding.

METALLOGRAPHY

Etchant: Alkaline ferricyanide solution

Combination: Tantalum to Rhenium
Number 42 (wire) (coupon)
0.062 gage 0.060

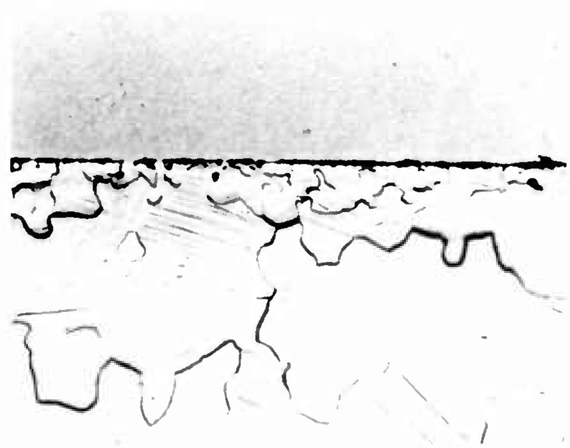
Longitudinal

Not Sectioned in Longitudinal Plane

Magnification:

Magnification:

Transverse



Magnification: 38X

Magnification: 250X

Comments: Profuse voids and general lack of bonding characterize this weld.

METALLOGRAPHY

Etchant: Unetched at 36X
KCN + $NH_4S_2O_8$ etch at 250X

Combination: Copper to Silver
Number 45 (Wire) (Coupon)
0.064 gage 0.060

Longitudinal

Magnification: 36X

Magnification: 250X

Transverse

Magnification: 36X
Reduced to 3/4 Size

Magnification: 250X

Comments: The edge-to-edge integrity of the joint and the degree of interpenetration of the mating surfaces exemplify a high degree of bond quality. No voids or unbonded areas were observed in these sections. Eccentric contact of the welding tip and wire resulted in deep indentation into the silver sheet along one edge (see lower left photomicrograph).

METALLOGRAPHY

Etchant: KCN + $NH_4S_2O_8$ + H_2O

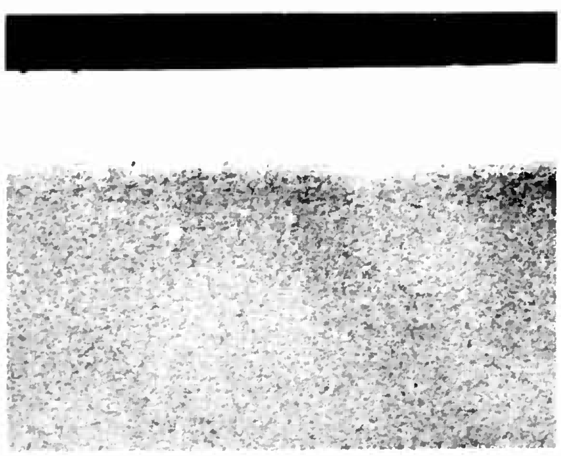
Combination: Gold to Silver
Number 46 (wire) (coupon)
0.060 gage 0.060

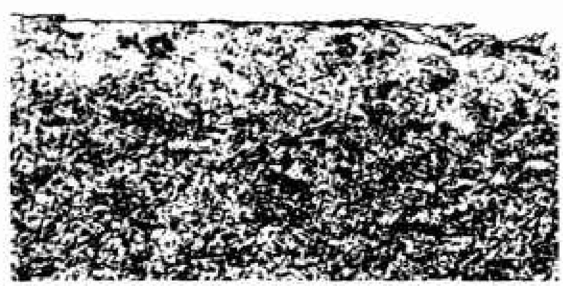
Longitudinal

Magnification: 36X

Magnification: 250X

Transverse





Magnification: 36X

Magnification: 250X

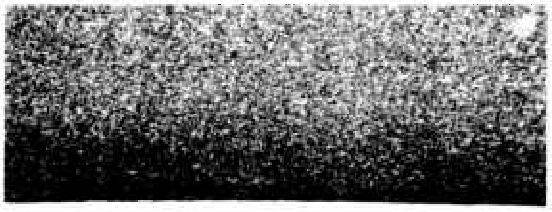
Comments: Severe flattening of the gold wire is evident. Bond quality is satisfactory.

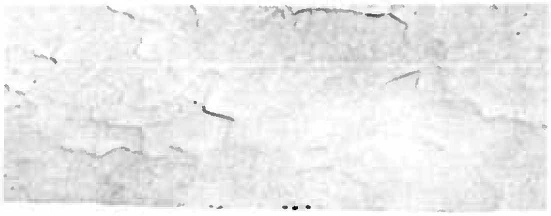
METALLOGRAPHY

Etchant: Unetched

Combination: Nickel to Silver
Number 47 (Wire) (Coupon)
0.060 gage 0.060

Longitudinal

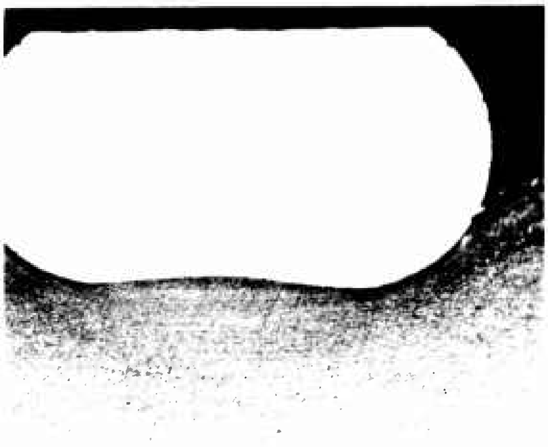




Magnification: 40X

Magnification: 250X

Transverse



Magnification: 40X
Reduced to 3/4 Size

Magnification: 250X

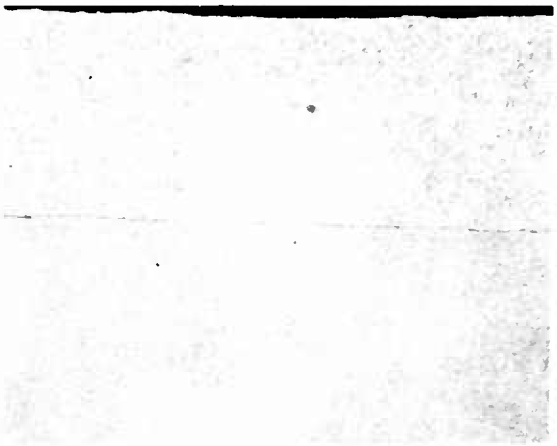
Comments: Bonding quality varies. The non-uniform deformation of the wire effected an unbonded area in the center. Edge bonding is satisfactory although numerous small voids are evident. The longitudinal section, taken along the edge of the wire, shows uniformly good bond quality.

METALLOGRAPHY

Etchant: $NH_4OH + H_2O_2$

Combination: Silver to Silver
Number 48 (wire) (coupon)
0.060 gage 0.060

Longitudinal

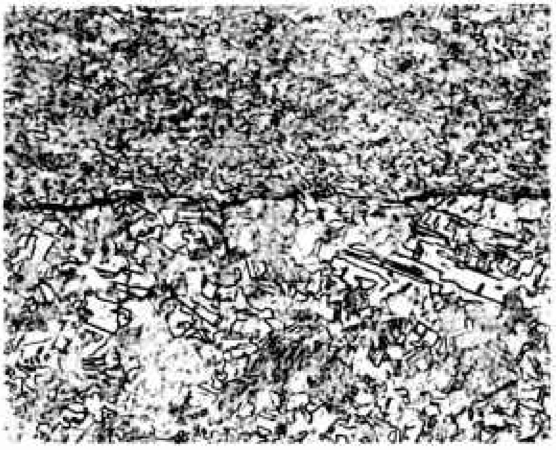


Magnification: 36X

Magnification: 250X

Transverse

Magnification: 36X



Magnification: 250X

Comments: Bonding appears satisfactory although some non-bond regions occur at the center (see upper right micro). The interface is outlined by residual oxide accumulations. The high thermal conductivity of silver apparently prevented local heating at the interface.

METALLOGRAPHY

Etchant: 1% Nital

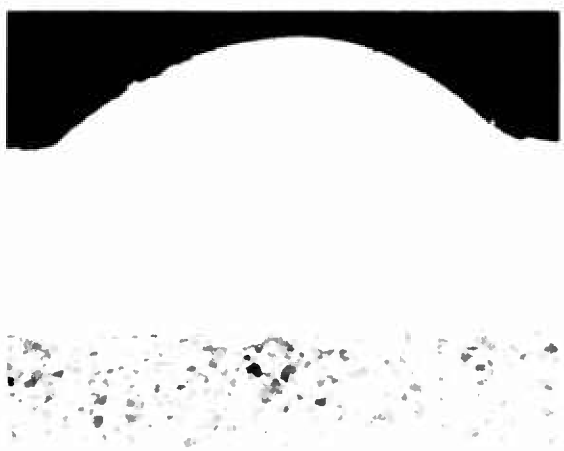
AISI 1010
Combination: Copper to Low Carbon Steel
Number 51 (wire) (coupon)
0.064 gage 0.0615

Longitudinal

Magnification: 38X

Magnification: 250X

Transverse



Magnification: 38X

Magnification: 250X

Comments: Bond is characterized by local areas of interpenetration and surface contiguity. Surface films are locally dispersed. Bond appears satisfactory except at edges (upper right photo).

METALLOGRAPHY

AISI 1010

Etchant:

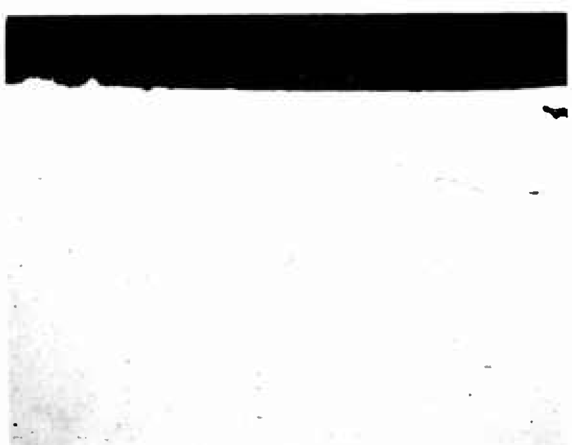
Combination: Gold to Low Carbon Steel
Number 52 (wire) (coupon)
0.060 gage 0.061

Longitudinal

Magnification:

Magnification: 250X

Transverse



Magnification:

Magnification: 250X

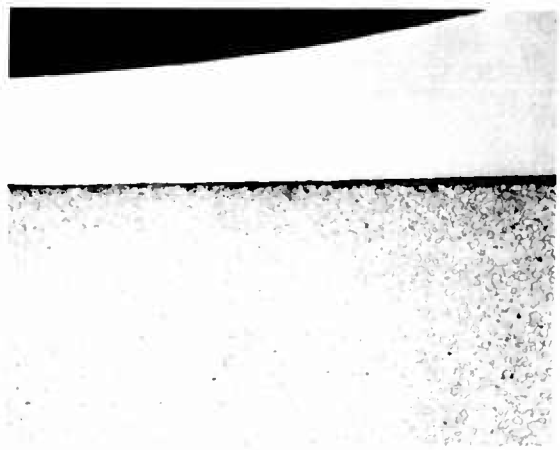
Comments: Bond interface contains microvoids and negligible dispersion of surface film. Good physical adhesion is indicated by the joint efficiency data.

METALLOGRAPHY

Etchant: 1% Nital (Nickel Unetched)

Combination: "A" Nickel to AISI 1010 L. C. Steel
Number 53 (wire) (coupon)
0.060 gage 0.062

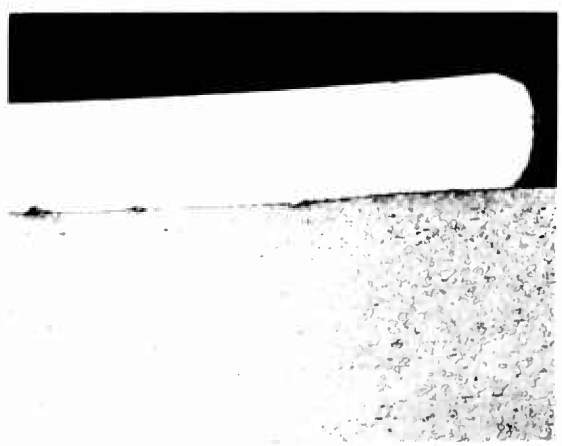
Longitudinal



Magnification: 32X

Magnification: 250X

Transverse



Magnification: 32X

Magnification: 250X

Comments: This bond displays very little interpenetration and non-uniform bond quality. Only superficial deformation of the mating surfaces has been produced at these welding conditions. Joint strength is satisfactory but improved bond quality would probably be achieved by modification of welding conditions.

METALLOGRAPHY

Etchant: 1% Nital

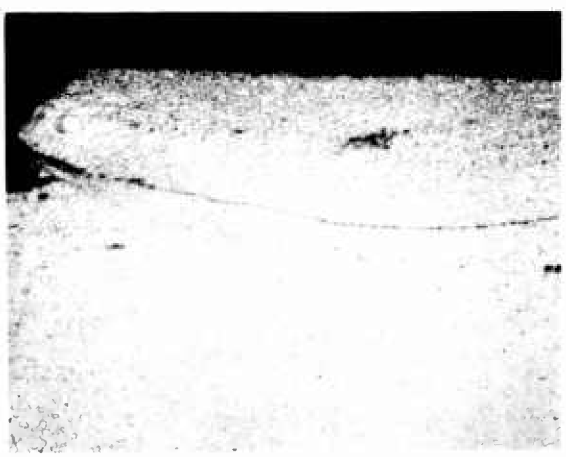
	AISI 1010 Low Carbon Steel (Wire)		AISI 1010 Low Carbon Steel (Coupon)
Combination: Number 55	AISI 1010 Low Carbon Steel (Wire)	to	AISI 1010 Low Carbon Steel (Coupon)
	0.062	gage	0.060

Longitudinal

Magnification: 36X

Magnification: 250X

Transverse



Magnification: 36X
Reduced to 3/4 Size

Magnification: 250X

Comments: Thermal effects are quite apparent. Sub-grain formation and recrystallization have occurred on the surface of the wire and along the bond interface. The recrystallized grains tend to assume a square block-like outline in the longitudinal section. The interface contains clusters of surface debris and small voids.

METALLOGRAPHY

Etchant: 1% Nital
(Stainless Steel Unetched)

Combination: Number 56

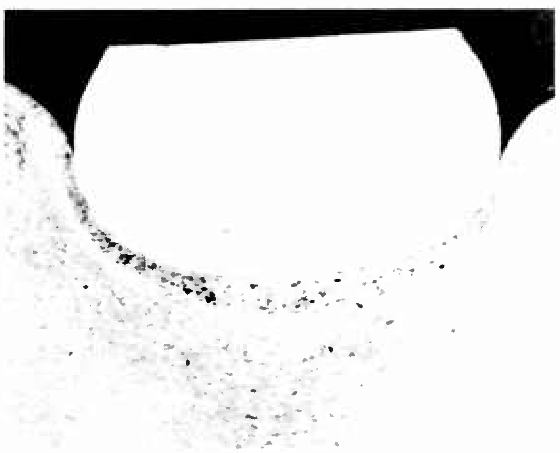
AISI 304 Stainless Steel (Wire)	to	AISI 1010 Low Carbon Steel (Coupon)
0.062	gage	0.060

Longitudinal

Magnification: 36X

Magnification: 250X

Transverse



Magnification: 36X
Reduced to 3/4 Size

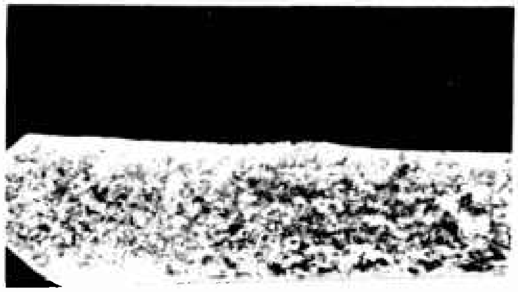
Magnification: 250X

Comments: This joint exhibits very good bond characteristics. The sub-grain formation and/or recrystallization hold evidence to the thermal effects in the carbon steel.

METALLOGRAPHY

Etchant:

Combination: Number 57 — Copper (wire) 0.064 gage to AISI 304 St. Steel (coupon) 0.060

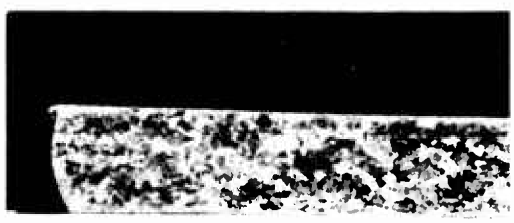


Not photographed at higher magnification

Magnification: 36X

Magnification: 250X

Transverse



Not photographed at higher magnification

Magnification: 36X

Magnification: 250X

Comments: Lack of intimate surface contact indicates inferior bonding.

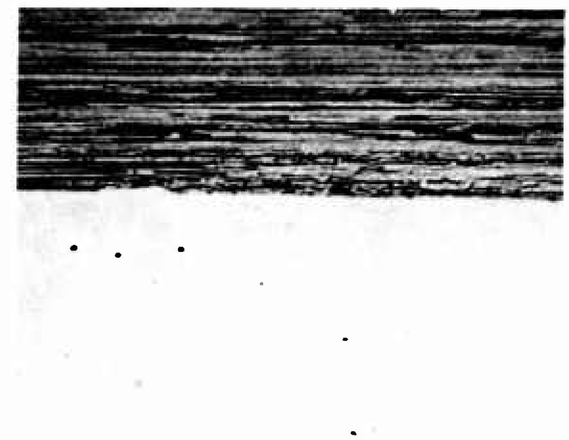
METALLOGRAPHY

Etchant: Alkaline ferricyanide solution

Combination: Molybdenum to AISI 304 St. Steel
Number 59 (wire) (coupon)
0.060 gage 0.060

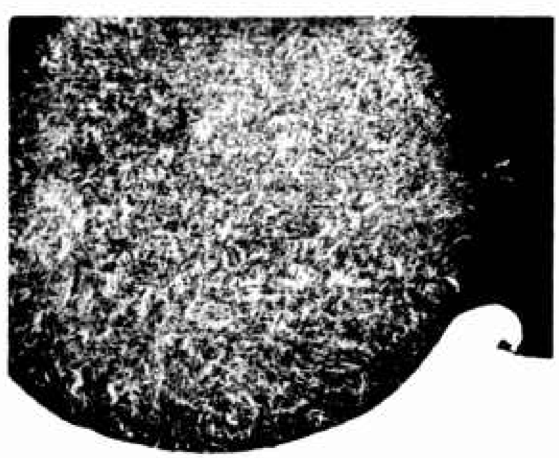
Longitudinal

Magnification: 45X



Magnification: 250X

Transverse



Magnification: 45X

Magnification: 250X

Comments: Satisfactory bond. No voids or separations were observed. Intimate contact of the faying surfaces exists along the bond line.

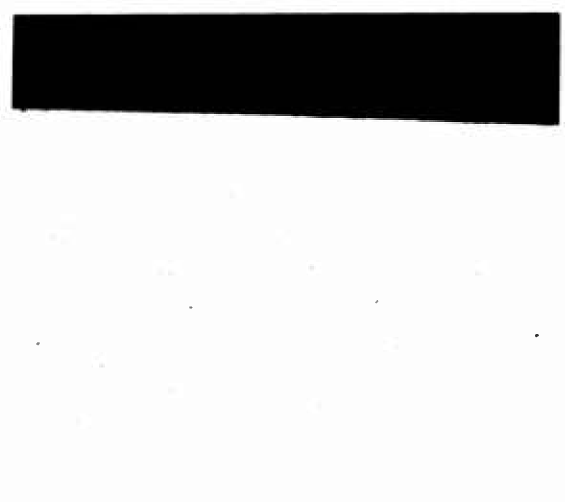
METALLOGRAPHY

AISI 304

Etchant: KCN + $NH_4S_2O_8$ + H_2O
(stainless steel unetched)

Combination: "A" Nickel to St. Steel
Number 60 (wire) (coupon)
0.060 gage 0.062

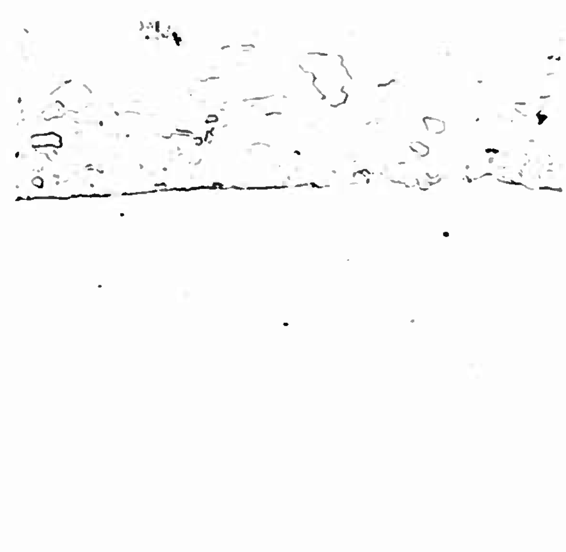
Longitudinal



Magnification: 32X

Magnification: 250X

Magnification: 32X



Magnification: 250X

Comments: The dark line delineating the interface resulted from etch attack. Bonding is satisfactory but only local areas of interpenetration were observed (lower right micro).

METALLOGRAPHY

Etchant: Alkaline ferricyanide solution

Combination: Number 61 — Rhenium (wire) 0.061 to AISI 304 St. Steel (coupon) gage 0.060

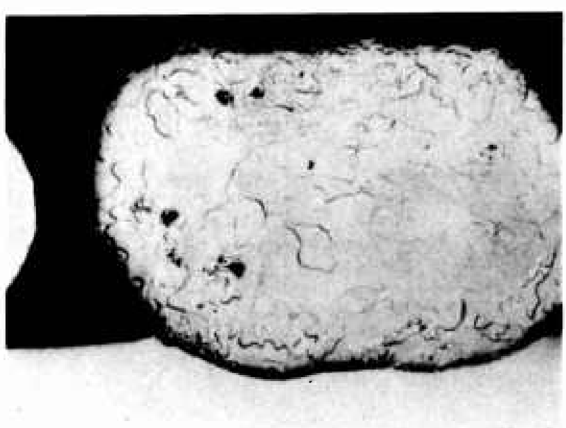
Longitudinal

Not Sectioned in Longitudinal Plane

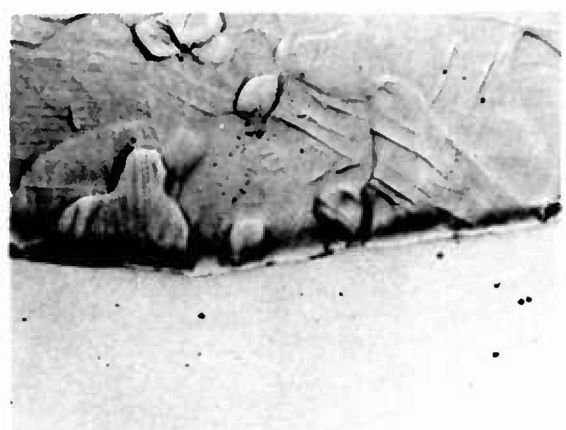
Magnification:

Magnification:

Transverse



Magnification: 38X



Magnification: 230X

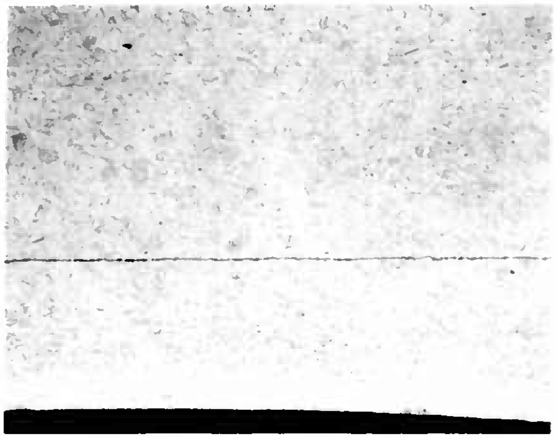
Comments: Non-bonds and intergranular separation of the rhenium wire are evident in micro at 250X. Wire contains abundant porosity. Bonded regions appear satisfactory and indicate the feasibility of welding this combination.

METALLOGRAPHY

Etchant: Oxalic Acid-Electrolytic

Combination: Number 64	AlSl 304 St. Steel (wire)	to	AlSl 304 St. Steel (coupon)
	0.0625	gage	0.060

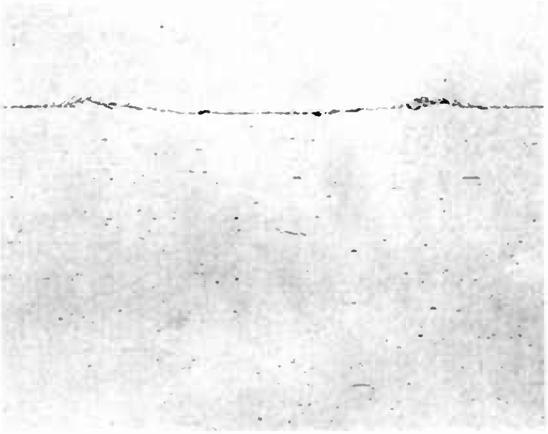
Longitudinal



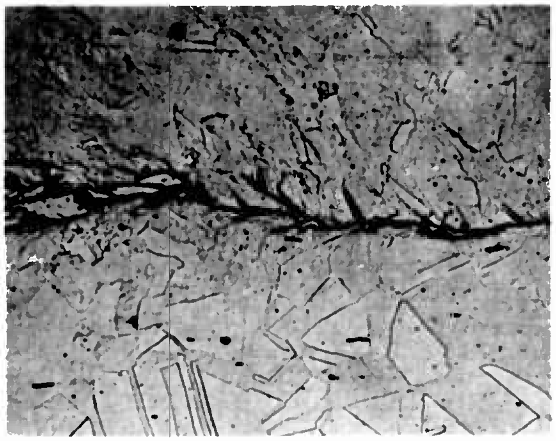
Magnification: 34X

Magnification: 250X

Transverse



Magnification: 34X



Magnification: 250X

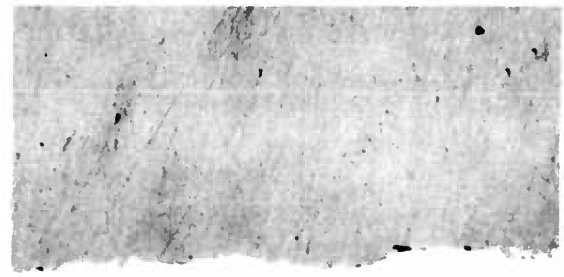
Comments: This weld, between similar materials, displays excellent bonding characteristics. The interface is outlined by a rapid etching constituent most probably a combination of dispersed oxide amid severely cold worked material. Note that the forked portions of the interface outline grain boundaries and indicate the flow pattern in this area.

METALLOGRAPHY

Etchant: Unetched

Combination: Number 65	Tantalum to (Wire)		AISI 304 Stainless Steel (Coupon)
	0.062	gage	0.060

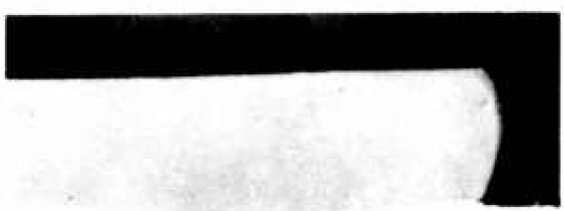
Longitudinal



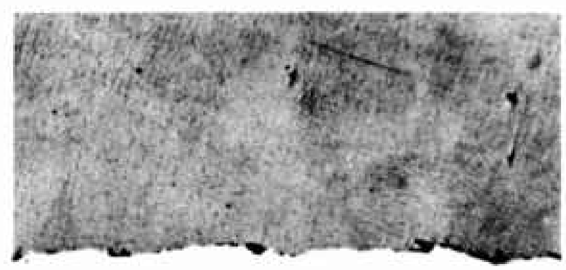
Magnification: 36X

Magnification: 250X

Transverse



Magnification: 36X
Reduced to 3/4 Size



Magnification: 250X

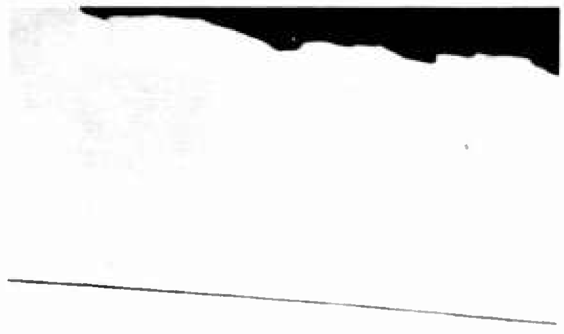
Comments: Small voids and clusters of accumulated oxide decorate the interface; elsewhere, integrity is excellent. Some of the interfacial debris may be non-metallic inclusions within the stainless steel. No positive identification is available.

METALLOGRAPHY

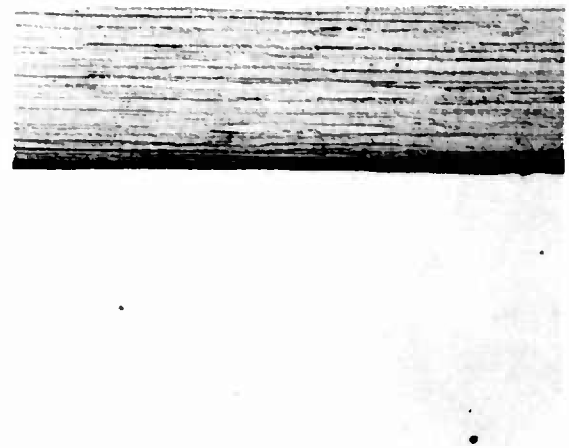
Etchant: Alkaline ferricyanide solution

Combination: Tungsten to AISI 304 St. Steel
Number 67 (wire) (coupon)
0.064-0.065 gage 0.060

Longitudinal

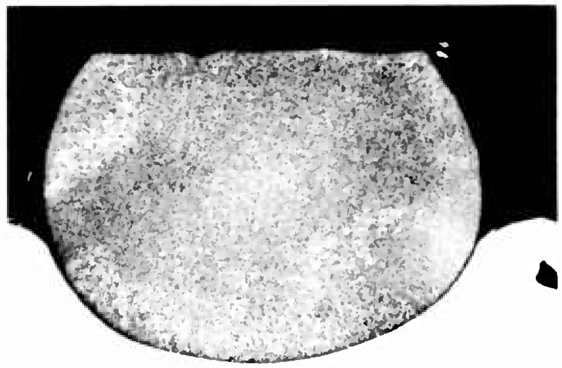


Magnification: 38X



Magnification: 250X

Transverse



Magnification: 38X

Magnification: 250X

Comments: Excessive polishing relief is evident in the longitudinal section; the transverse section indicates satisfactory bonding. The surface of the tungsten wire was flattened and roughened, but no cracks were observed in these sections.

METALLOGRAPHY

Etchant: Unetched

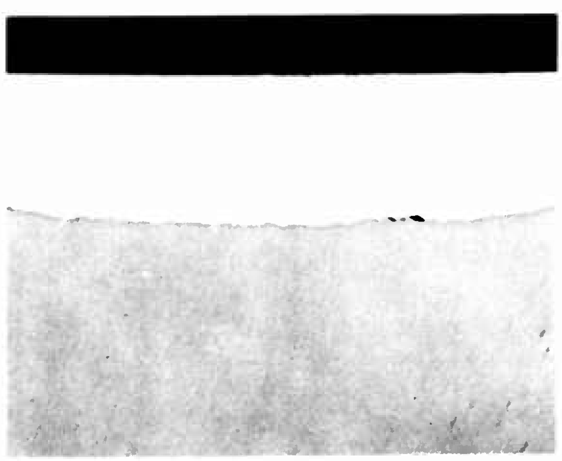
Combination: Number 70 — Nickel (Wire) 0.060 to Tantalum (Coupon) 0.062 gage

Longitudinal

Magnification: 36X

Magnification: 250X

Transverse



Magnification: 36X
Reduced to 3/4 Size

Magnification: 250X

Comments: Only a few scattered unjoined areas were observed. As a whole, the joint exhibits good interpenetration and integrity of the mating surfaces.

METALLOGRAPHY

Etchant: Alkaline ferricyanide solution

Combination: Number 71 — Rhenium (wire) 0.060 to Tantalum (coupon) gage 0.062

Longitudinal

Not Sectioned in Longitudinal Plane

Magnification:

Magnification:

Transverse

Magnification: 38X

Magnification: 250X

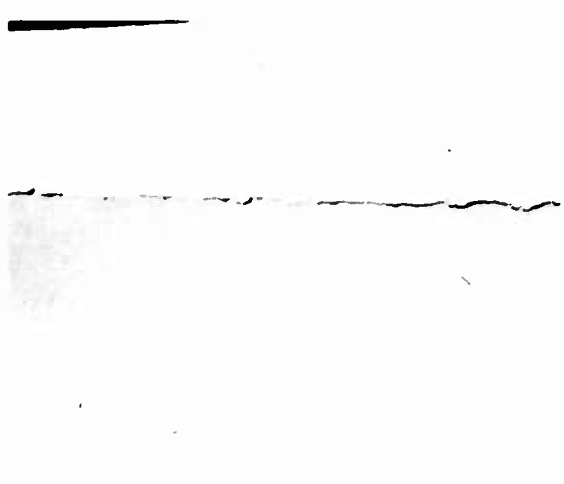
Comments: Bond quality appears satisfactory except at edges of weld. Rhenium wire is porous.

METALLOGRAPHY

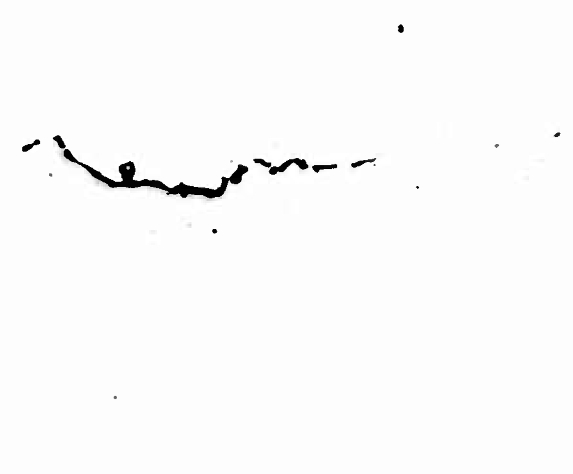
Etchant:

Combination: Number 72 — AISI 304 St. Steel (wire) 0.0625 to Tantalum (coupon) 0.062 gage

Longitudinal



Magnification: 36X



Magnification: 250X

Transverse

Magnification: 36X

Magnification: 250X

Comments: Voids and separation at the interface result in an unsound and therefore unsatisfactory weld. That excellent bond quality can be attained is indicated by the high degree of interpenetration evident in this weld.

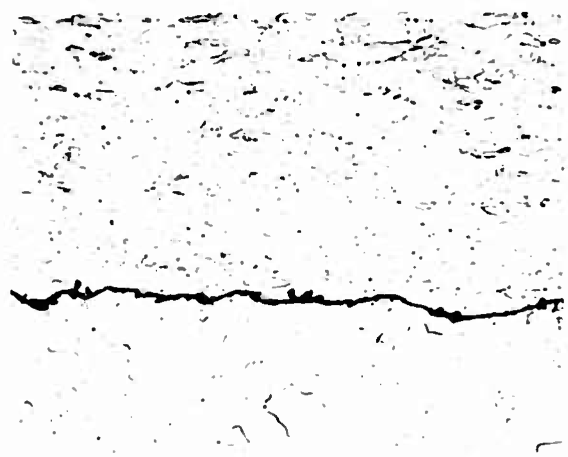
METALLOGRAPHY

Etchant: HF + HNO_3 + Lactic Acid

Combination: Tantalum to Tantalum
Number 73 (wire) (coupon)
0.062 gage 0.062

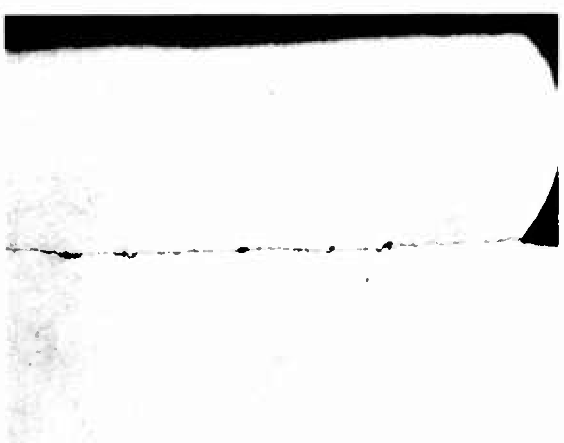
Longitudinal

Magnification: 52X

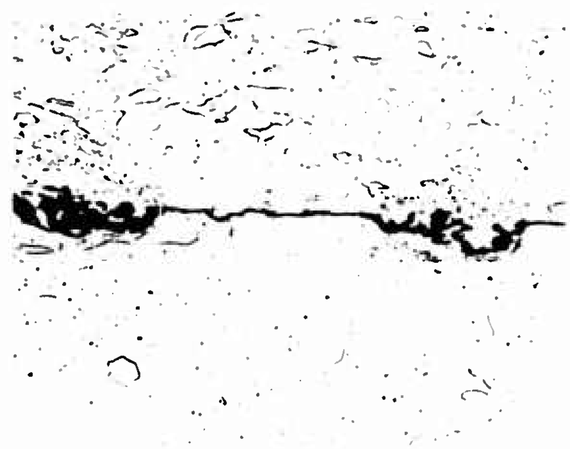


Magnification: 250X

Transverse



Magnification: 52X



Magnification: 250X

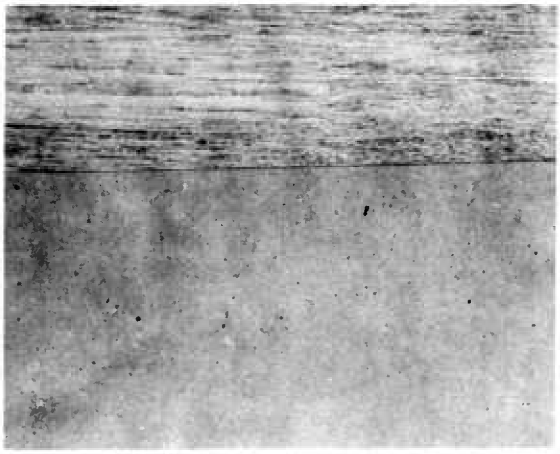
Comments: The weld interface is revealed by a rapid-etching constituent which cannot be identified or resolved under the microscope. Very likely a mixture of dispersed surface films and/or severely cold worked material is responsible for this appearance. Joint integrity is very good, and the excellent strength data attests to the quality of the bonding.

METALLOGRAPHY

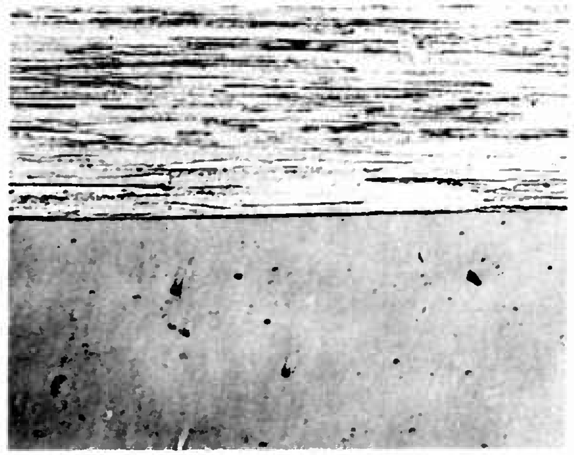
Etchant: KOH + $K_3Fe(CN)_6$
(Tantalum Unetched)

Combination: Tungsten to Tantalum
Number 75 (Wire) (Coupon)
0.064 to 0.066 gage 0.063

Longitudinal

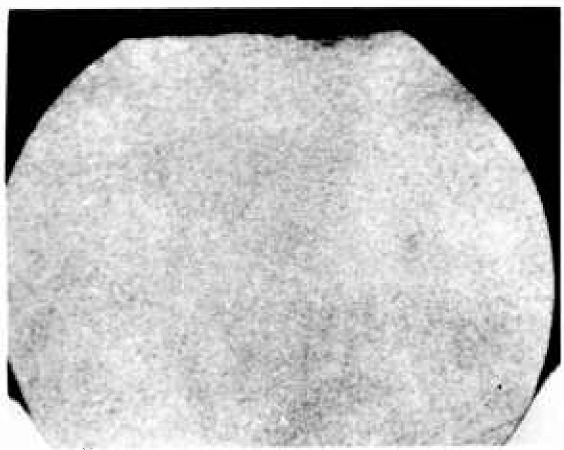


Magnification: 55X

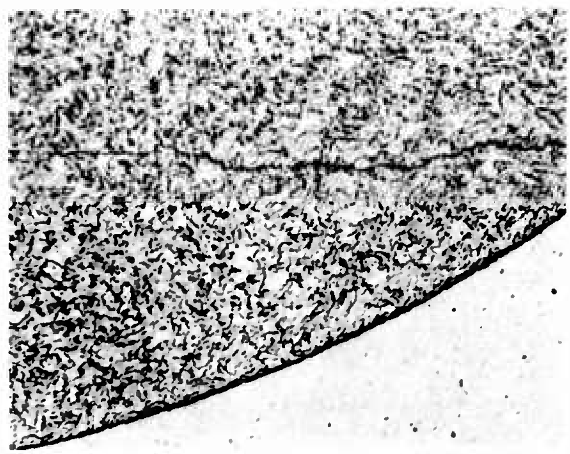


Magnification: 250X

Transverse



Magnification: 55X
Reduced to 3/4 Size



Magnification: 250X

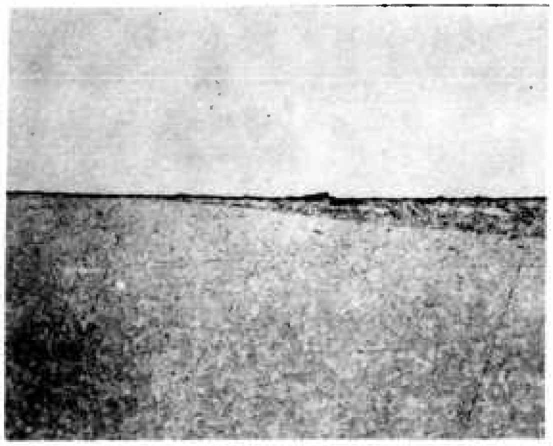
Comments: Metallographically, bond quality proved difficult to determine because of the interface relief. No large voids were observed; the surfaces appeared to be in intimate contact. Note the crack in the tungsten wire.

METALLOGRAPHY

Etchant: $HNO_3 + HF + H_2O$
(stainless steel unetched)

Combination Number 77: AISI 304 St. Steel (wire) to Titanium (coupon)

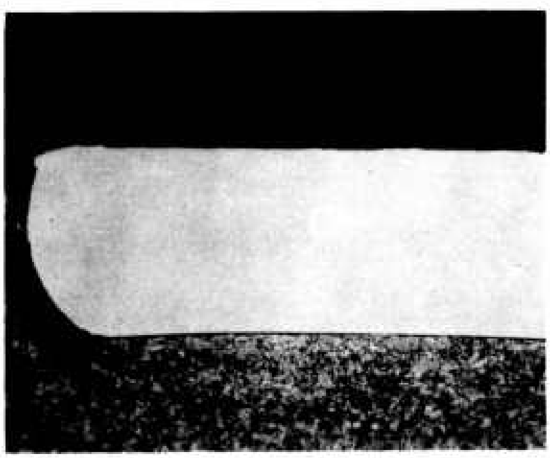
Longitudinal



Magnification: 34X

Magnification: 250X

Transverse



Magnification: 34X

Magnification: 250X

Comments: A recrystallized zone in the titanium surrounds the bond interface. Local etching attack at the interface exaggerates the width of the bond line. Bonding quality is unsatisfactory in transverse section.

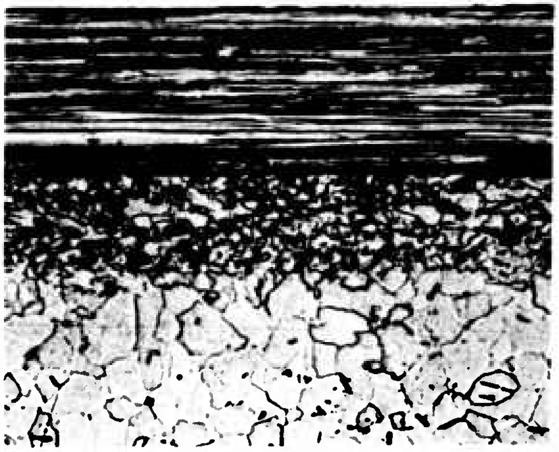
METALLOGRAPHY

Etchant: Alkaline ferricyanide etch

Combination: Molybdenum to Titanium
Number 79 (wire) (coupon)
0.060 gage 0.062

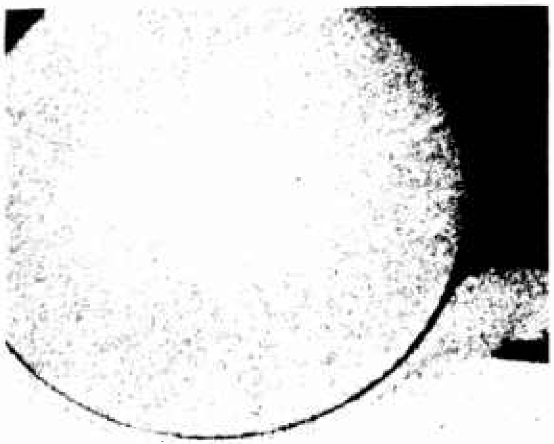
Longitudinal

Magnification: 44.5X

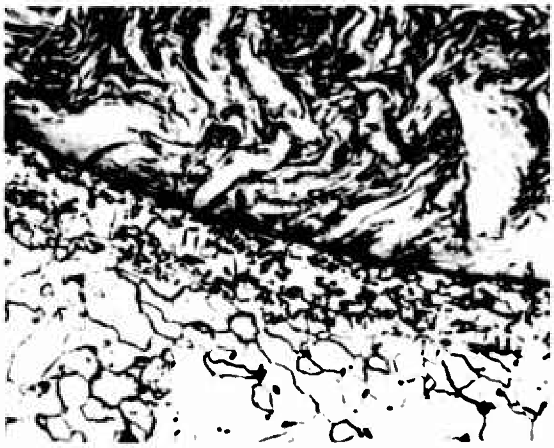


Magnification: 250X

Transverse



Magnification: 44.5X



Magnification: 250X

Comments: Bonding resulted in a thin bond of recrystallization in the titanium sheet. Width of the bond line is exaggerated by etching. Lack of interpenetration of faying surfaces was observed. Good bonding.

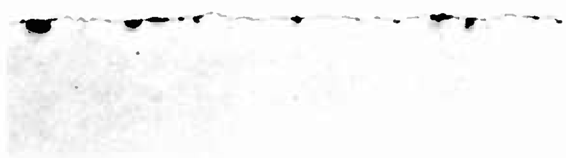
METALLOGRAPHY

Etchant: Unetched

Combination: "A" Nickel to Titanium
Number 80 (wire) (coupon)
0.060 gage 0.070

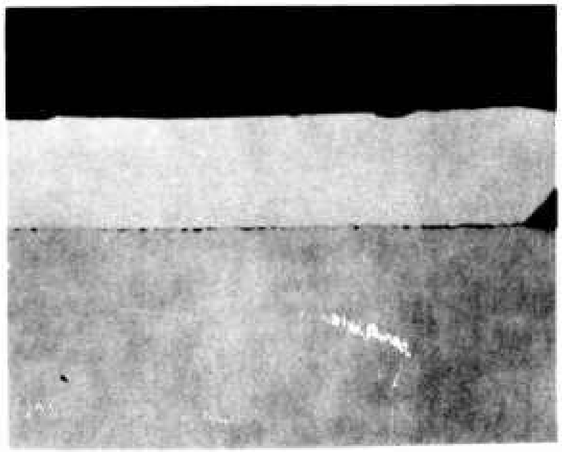
Longitudinal

Magnification: 32X

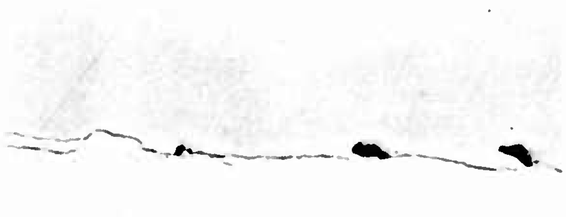


Magnification: 250X

Transverse



Magnification: 32X



Magnification: 250X

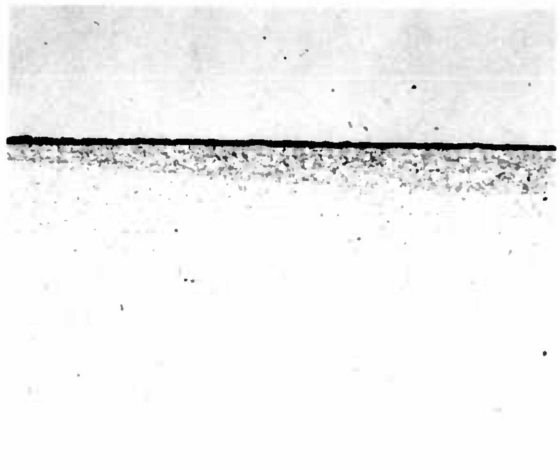
Comments: Although deformation of the nickel wire is severe, mutual interpenetration of the faying surfaces has not been sufficient to prevent interfacial void formation. Bonding in areas of contact is satisfactory, but the weld as a whole is unsatisfactory because of the discontinuous character of the bonding.

METALLOGRAPHY

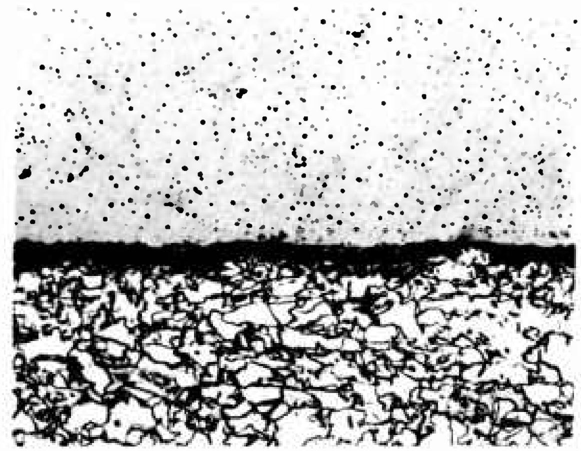
Etchant: $HNO_3 + HF + H_2O$

Combination: Number 81 — Tantalum (wire) 0.062 gage to Titanium (coupon) 0.070

Longitudinal

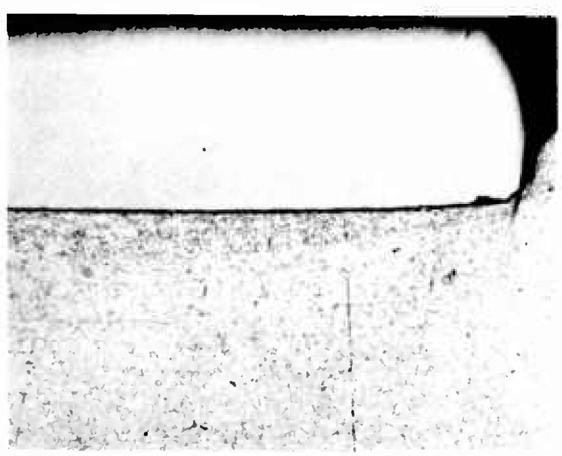


Magnification: 36X



Magnification: 250X

Transverse



Magnification: 36X

Magnification: 250X

Comments: The tantalum wire was flattened and impressed into the titanium sheet resulting in a plane interface. The formation of alloy layers is evident. Since the diffusion layers are continuous, weld quality can only be judged by the characteristics of the (unknown) alloy phases.

METALLOGRAPHY

Etchant: $HNO_3 + HF + H_2O$

Combination: Number 82 — Titanium (wire) 0.063 to Titanium (coupon) gage 0.070

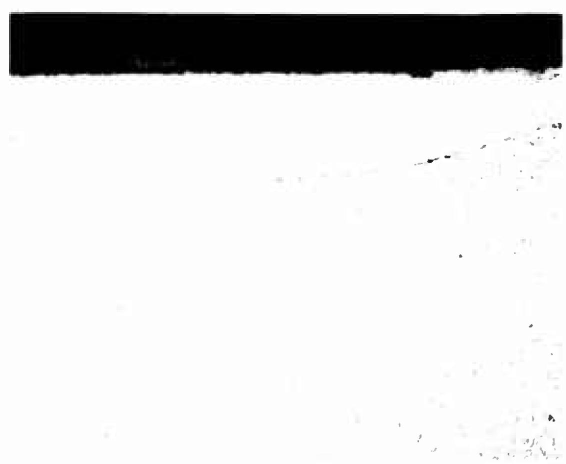
Longitudinal

Not Sectioned in Longitudinal Plane

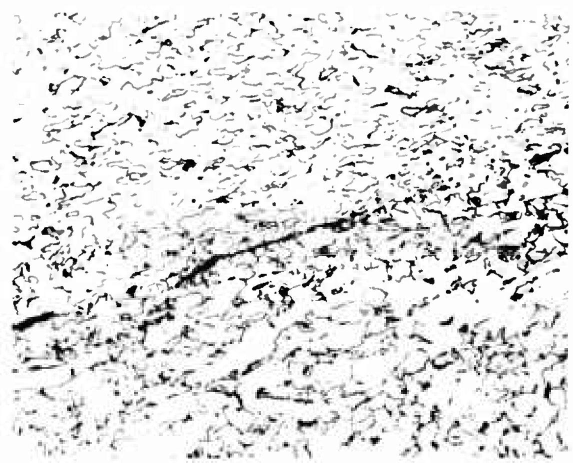
Magnification:

Magnification:

Transverse



Magnification: 32X



Magnification: 250X

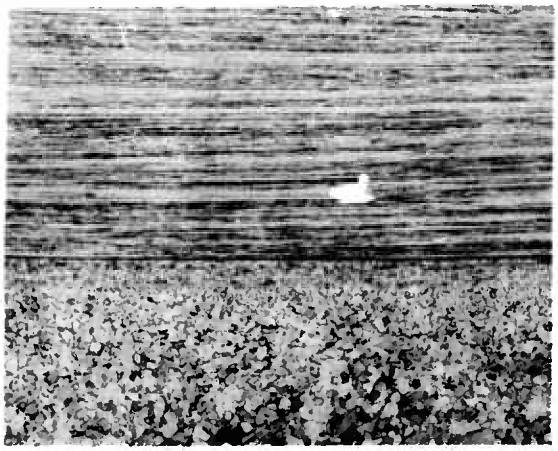
Comments: The partially recrystallized zone in the sheet and wire indicate that substantial heating occurred during formation of the weld. Bonding is good with many areas of complete structural continuity across the interface. The interface is delineated by the rapid-etching oxide-laden film.

METALLOGRAPHY

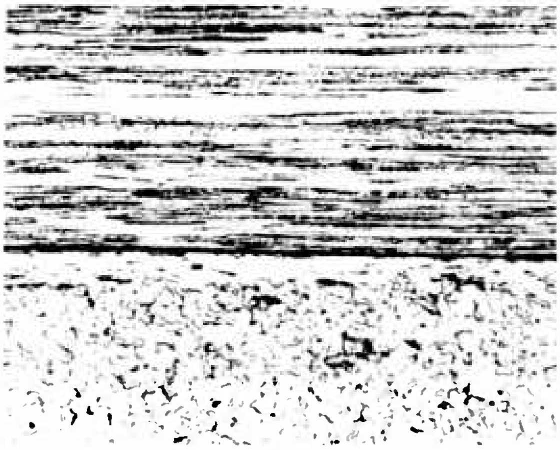
Etchant: Alkaline ferricyanide solution(w)
$HF + HNO_3 + H_2O$ (Ti)

Combination: Tungsten to Titanium
Number 83 (wire) (coupon)
0.064-0.066 gage 0.063

Longitudinal

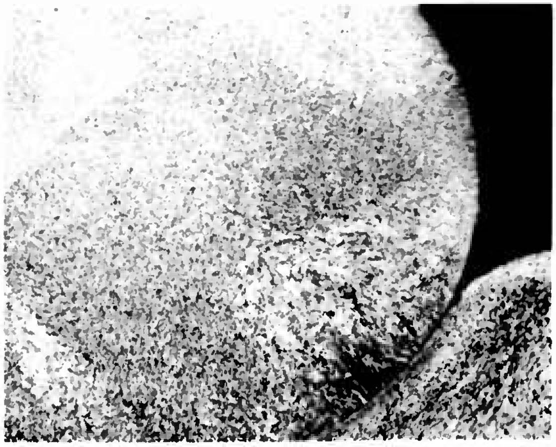


Magnification: 59X



Magnification: 250X

Transverse



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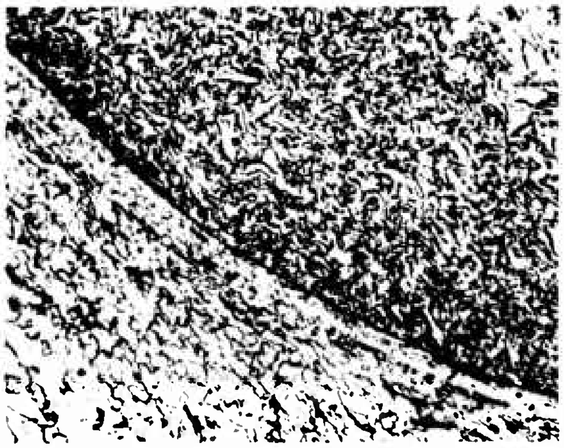


Magnification: 250X

Comments: The titanium sheet has been locally recrystallized adjacent to the interface. Bond quality is satisfactory.

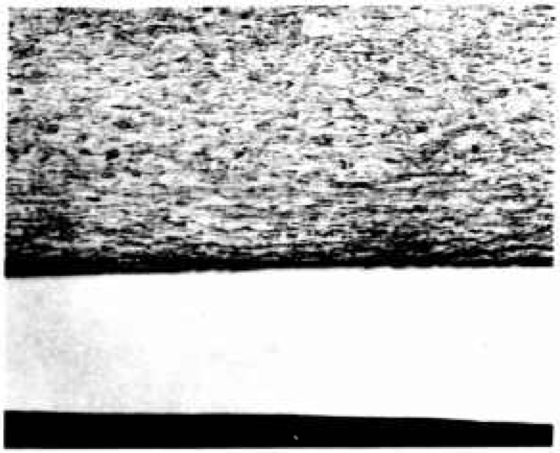
METALLOGRAPHY

Etchant: Alkaline ferricyanide solution

Combination: "A" Nickel to Tungsten
Number 86 (wire) (coupon)

0.060 gage 0.063

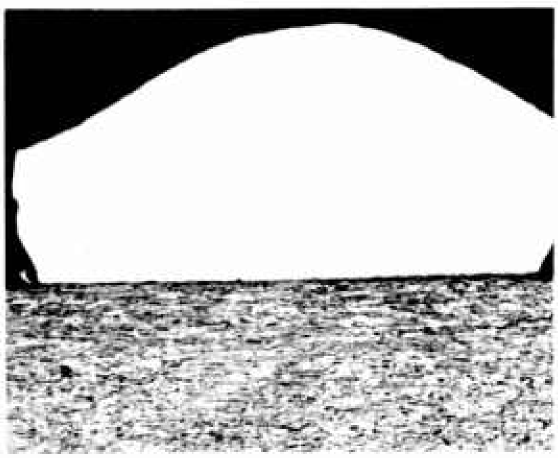
Longitudinal



Magnification: 38X

Magnification: 250X

Transverse



Magnification: 38X

Magnification: 250X

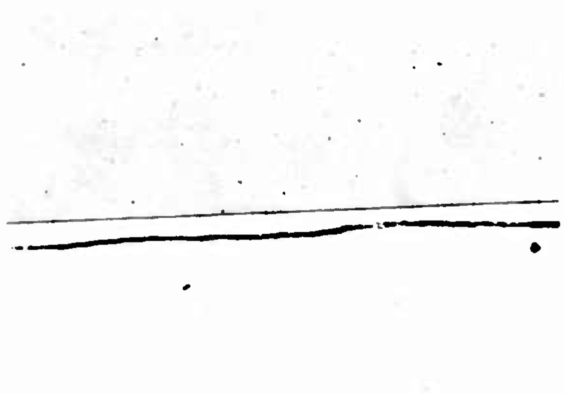
Comments: Cracks in the tungsten sheet parallel to the weld plane are evident in the micros. Bonding is satisfactory.

METALLOGRAPHY

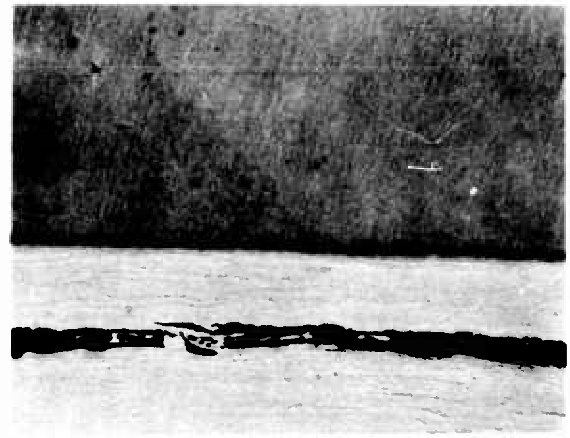
Etchant: Alkaline ferricyanide solution

Combination: Number 89 — Tantalum (wire) 0.062 to Tungsten (coupon) gage 0.058-0.061

Longitudinal



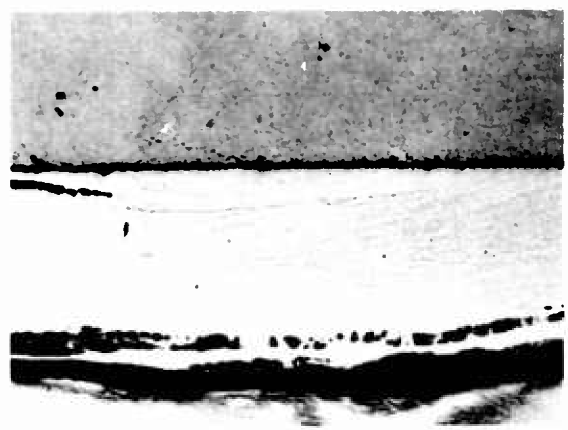
Magnification: 48X



Magnification: 250X

Transverse

Magnification: 48X



Magnification: 250X

Comments: Unsatisfactory bonding with catastropic cracking in the tungsten sheet beneath the contact surface.

METALLOGRAPHY

Etchant: Alkaline ferricyanide solution

Combination: Tungsten to Tungsten
Number 91 (wire) (coupon)
0.055-0.057 gage 0.060

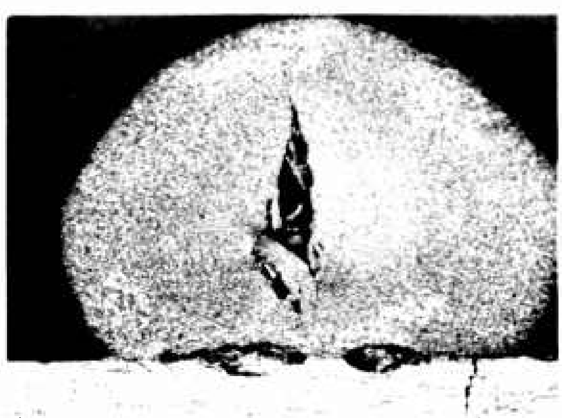
Longitudinal

(Not photographed at higher magnification)

Magnification: 36X

Magnification:

Transverse



(Not photographed at higher magnification)

Magnification: 36X

Magnification:

Comments: The tungsten wire is split through the center and the sheet is cracked in the weld region. Unsatisfactory welding.

METALLOGRAPHY

Combination: Number 3A — Molybdenum (wire) 0.0008 gage to Copper (coupon) 0.005

Unetched 1000X

Comments: Bond quality is difficult to ascertain with certainty because of polishing relief at the interface. The wire is mechanically interlocked to the surface, but bond quality is questionable.

Combination: Number 11A — Tungsten (wire) 0.0003 gage to Copper (coupon) 0.055

Unetched 1000X

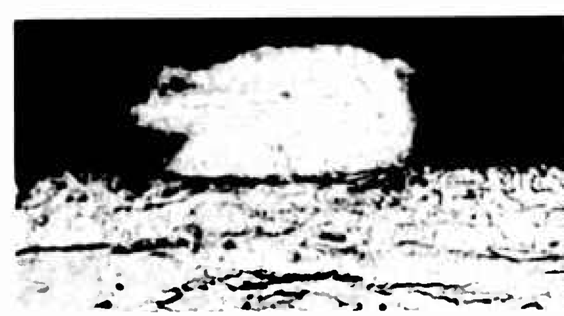
Comments: Simple impression and separation of the hard tungsten wire into the softer copper sheet is shown. No bonding (except perhaps mechanical interlocking) was achieved.

Combination: Number 77A — AISI 304 Stainless Steel (wire) 0.001 gage to Gold (coupon) 0.060

Unetched 1000X

Comments: Mechanical joining only is shown here. The sliver of gold on the flat surface of the stainless wire apparently was transferred from the welder sonotrode tip.

Combination: Number 24A — Titanium (wire) 0.001 gage to Molybdenum (coupon) 0.060

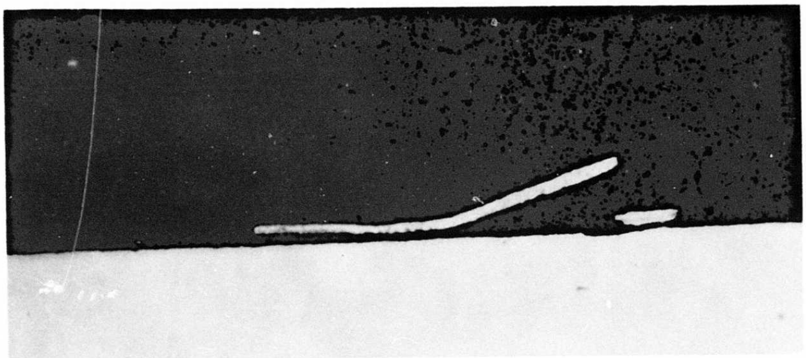


Etchant: $KOH + K_3Fe(CN)_6$ 1000X

Comments: Moderate deformation of the titanium wire and non-bond areas characterize this weld section. Etching has exaggerated the interface and revealed several microcracks in the molybdenum at the edge of the weld.

METALLOGRAPHY

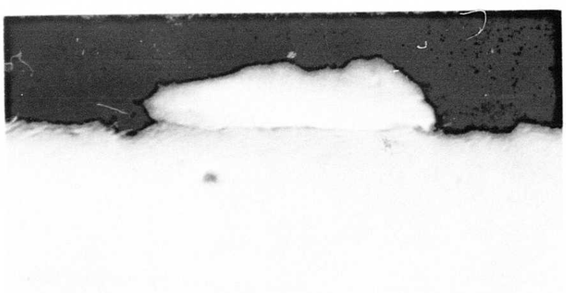
Combination: Gold to Nickel
Number 27A (wire) (coupon)
0.0003 gage 0.060



Unetched 1000X

Comments: Extreme flattening of the wire, shown in this (transverse) section, was observed without penetration of the oxide surface film on the nickel sheet. Adhesion between the wire and the surface film was sufficiently strong to withstand handling and metallographic preparation although half of the bond has separated. This type of adhesion is unsuitable for electrical connections.

Combination: Molybdenum to Rhenium
Number 38A (wire) (coupon)
0.008 gage 0.060



Unetched 1000X

Comments: The molybdenum wire was deformed without cracking during welding. Intimate surface contact indicates a satisfactory weld for this combination.

Combination: AISI 304 Stainless Steel to Silver
Number 50A (wire) (coupon)
0.001 gage 0.060

Unetched 1000X

Comments: The wire is both bonded and impressed into the sheet surface except in the area near the surface.

METALLOGRAPHY

Combination: Titanium to AISI 304 Stainless Steel
Number 66A
(wire) (coupon)
0.001 gage 0.060

Unetched 1000X

Comments: The specimen is not bonded. Metal fragments (grinding debris) have lodged in the void between the wire and sheet. The wire was apparently only impressed into the surface of the sheet without substantial bonding of the faying surfaces.

Combination: Molybdenum to Tantalum
Number 69A
(wire) (coupon)
0.0008 gage 0.060

Unetched 1000X

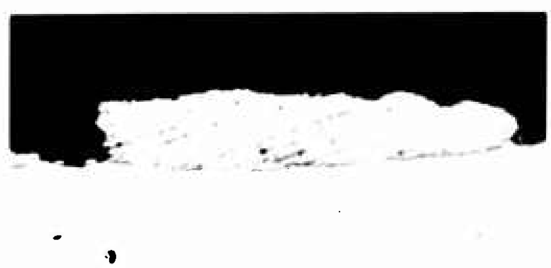
Comments: Good bonding is indicated along the base of the deformed molybdenum wire. Voids exist at the edges of the wire. No microcracks were observed in the flattened molybdenum wire.

Combination: Copper to Titanium
Number 78A
(wire) (coupon)
0.0005 gage 0.067

Unetched 1000X

Comments: The softer copper wire has been severely deformed during welding. Note the similarity of the wire surface and interface contour. Bond quality appears satisfactory.

Combination: Titanium to Tungsten
Number 90A
(wire) (coupon)
0.001 gage 0.056



Unetched 1000X

Comments: This weld section illustrates satisfactory bonding. The deformation of the wire afforded a larger contact area and reduced the thickness of the weld member. Comparison of this micro with the Ti/Mo section (Comb. #79) indicates that similar bonding behavior could be achieved with a change in welding machine settings.

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